Manual of forest inventory

With special reference
to mixed tropical forests

Reprinted 1992

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FOREWORD

The Forestry Department (formerly Forestry and Forest Products Division) of the Food and Agriculture Organization of the United Nations has been involved since this Organization's inception in the definition and implementation of forest resource evaluation programmes, at all levels, from world and regional forest appraisals to local management inventories. It has performed a number of forest resource surveys in many countries of the world, has carried out a series of world and regional studies - such as the World Forest Inventory and the regional timber trends and prospects studies - and has produced a few publications on the methodology side such as "Planning a Forest Inventory" by Dr. B. Husch, and the "Manual for forest inventory operations executed by FAO" (1967).

To take the experience gained by FAO in the last few years into account and to fulfil in this field FAO's role concerning dissemination of knowledge, Mr. J.P. Lanly, Forest Resource Surveys Officer, was asked to write a new manual of forest inventory. This manual is intended to be of use mainly to professionals dealing with the evaluation and management of mixed tropical forests, since it is restricted to inventory methods and practices which have been found feasible in these areas.

At the beginning of 1972 about thirty specialists all over the world were asked to give their comments on a draft of the outline and of the main contents. Most of their suggestions have been taken into consideration. They must all be thanked here, with a particular mention of Dr. P.G. de Vries from Wageningen University in the Netherlands who made the most substantial proposals. The sections of Chapter V devoted to measurement and volume estimation techniques formed the basis of lectures delivered by Mr. J.P. Lanly at the training course on forest inventory organized in August and September 1973 by the Royal College of Forestry in Stockholm in cooperation with FAO, and include information on recovery studies and accessibility problems, two topics which need to be given more consideration in future inventory work. The section on accessibility problems was reviewed by Prof. U. Sundberg, Chief of the Forest Logging and Transport Branch of the Forest Resources Division, and Chapter VI on data recording and processing was drafted by Dr. H.E. Marsch of the Forest Management Branch. Thanks are due also to Messrs. R. Bolton, J.W. Eastwood, J. Jackson and D.A. Harcharik for their contribution to the editing of the English version and to Mrs. R.S. Borelli for her secretarial help.

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INTRODUCTION

1 Historical background

During the period 11-22 September 1967, a meeting of forest inventory experts attached to UNDP/SF projects was held at FAO Headquarters in Rome (1). The purpose of this meeting was the improvement of FAO's inventory operations with the following four main objectives in view:

1) In the light of experience, to clarify the basic forest resource information needed for potential forest industry investors and to use this knowledge in guiding present and future projects.

2) To achieve greater uniformity and standardization in the form of inventory results being obtained, while still leaving latitude for specialized information that might be required to meet local conditions. This would facilitate the comparing and combining of the resource data obtained on different inventories.

3) To improve the efficiency of inventory operations so that better and more reliable forest resource information can be obtained at lower cost.

4) To intensify the cooperation and collaboration between forest inventory specialists and the users of inventory results so that more pertinent inventory information can be obtained.

As a result of this meeting, a recommendation was made that the present manual be prepared to assist inventory experts in the planning and execution of project inventory work.

The first edition of the Manual was prepared by B. Husch, the former Chief of the Forest Resources Survey Section of the FAO Forestry Department, and incorporated the recommendations of the meeting.

In that first edition it was stated that "a manual of this type should be a working document subject to periodic modification or revision to incorporate improvements which will become evident in the course of its use". A revision of the manual was undertaken during 1972. A questionnaire was sent to a number of inventory specialists, together with a general outline and the main contents of the proposed revision, asking for review and suggestions. Most of them replied and gave us many valuable suggestions regarding information to be included in the new edition. The main emphasis was on the definition of the purposes of the inventory, the accuracy of the measurements and data processing procedures. We wish to thank them here for their kind collaboration, without which this edition would have omitted certain important items and its preparation would have been much more difficult.

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(1) A report of this meeting is given in document FO:SF/7, IM 17 dated 9 October 1967 and entitled "Report of the Headquarters Meeting of Forest Inventory Experts on UNDP/SF Projects".

2. Main features of this new edition

a) This document is a manual. Its purpose is not to be a comprehensive textbook on forest inventory but to list and describe briefly the main tools which are used in this important field of forest activity and to give advice on their use. It does not seek to provide detailed practical instructions for use by technicians and workers, as each inventory has its own requirements in this respect and needs its own special instructions.

This manual obviously cannot suffice for all purposes and a number of questions remain unanswered. The information given should be supplemented by information taken from other sources such as statistical and forestry textbooks and periodicals, inventory reports as well as from individual research and reasoning. Each inventory operation, with its own purposes and requirements, must have its own specifications. One cannot imagine a single book which provides an answer for all cases.

b) The manual, in the first edition, was entitled "Manual for forest inventory operations executed by FAO". It cannot be claimed, however, that inventories executed by FAO are any different from those executed by public agencies or private firms, and this manual takes into account some forest inventory techniques used by specialists outside FAO. Moreover, one has to consider the role that FAO plays in training and dissemination of information; this manual may be of use not only within the framework of FAO inventory operations but also in many developing countries where there is a lack of relevant expertise. For these reasons, reference to FAO inventory operations has been suppressed in the new title.

c) Inventories carried out by FAO or developing countries are most often in tropical regions. Although this manual deals with forest inventory in general, most consideration is given to inventories of broadleaved tropical forests. These are of special interest for most of the developing countries with forest areas. As they are of less use for tropical forests some interesting techniques used in temperate zones, such as photogrammetric measurements, photo volume tables and point sampling methods, are only briefly described. However, these techniques may assume increasing importance for plantations and homogeneous natural stands in many developing countries.

d) Almost all forest inventories in developing countries are carried out for the evaluation of wood resources with emphasis on estimation of gross volumes, quality assessment and utilization studies. However one must not forget that there may be other data to collect and other parameters to estimate according to the purposes of the inventory.

CHAPTER II

PURPOSE AND PLANNING OF A FOREST INVENTORY

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PURPOSE AND PLANNING OF A FOREST INVENTORY

The main components of a forest inventory and the programming depend upon the aims of the operation. Purpose and planning are closely related; purpose must be clearly defined and planning designed to achieve that purpose. For this reason they are put together in this chapter. Further comments regarding these matters will be found in "Planning a Forest Inventory", by B. Husch (FAO Forestry and Forest Products Studies No. 17).

1 Purpose of the inventory

11 Introduction

It is very important to define clearly the various objectives of the proposed inventory. The relative importance of each must be considered, in order to design and implement an operation which best solves the problem. Account must also be taken of the unavoidable constraints and limitations such as available time and funds and ability of the staff.

A usual criticism made to the people responsible for designing and executing inventory operations is that they undertake such work without a clear idea of the objectives to be met and thus provide forestry officers, economists, loggers and industrialists with inadequate or even useless information.

Sometimes a thorough study of the problem may indicate that inventory will not provide the correct answer. A cost benefit analysis may also conclude that a forest inventory is not the most efficient tool for providing the information required due to existing constraints and limitations. Compilation of information already available, comparison with other similar stands already inventoried and use of research results, may meet the required degree of precision at less expense.

There may be, at the same time and in the same country, a need for different kinds of inventory, for instance inventory at a country-wide level ("national forest inventory"), inventories of big units of forest area (for instance 100,000 ha of forest) or inventories of stands for the preparation of working plans. But, as an example, it cannot be expected that information obtained from a national forest inventory will be adequate to form the basis of a detailed local management plan. This has to be pointed out to the decision-makers who sometimes believe that a single type of forest inventory will provide them with all the information they need at different levels. Generally, for lack of resources, priority has to be given to that type of inventory which will solve the more urgent problems.

Sometimes a careful study may demonstrate that the most useful operation to be carried out is a combination of partial inventories at the various levels. Recently a request to UNDP/SF for a national forest inventory was converted into a combination of the following operations:

- reconnaissance by photointerpretation and some field plots of the forested area of the country, for an estimation of the areas covered by each vegetation and forest type;

- vegetation mapping of a selection of forest reserves, with complementary field plots for rough estimation of the growing stock of each fórest type;

- intensive inventory, with vegetation mapping, of the most valuable forest area.

This example shows that a forest inventory programme may include different types of inventory in order to meet different objectives.

12 Definition of the objectives

121 The objectives must be defined jointly by the people who will make use of the inventory results (e.g. decision-makers, forest managers) and by the inventory specialist, not by the latter alone. The inventory specialist should design an inventory which will provide the users with the information they need in a suitable form and with the required precision. This cooperation with the potential users is necessary from the time that the inventory is prepared until the delivery of the final results.

Regarding this cooperation two difficulties may be encountered:

a) In certain cases the inventory specialist has to prepare the inventory at a time when the users are either not present or do not have a clear and definitive idea of the information needed. For instance, in a forestry development project, management, logging and economics advisers may arrive only after the inventory has started or has even been completed, because they cannot function effectively until the information provided by the inventory is available. Usually they do not participate in the preparation of the inventory, and this may explain why the information given by the inventory is inadequate in some cases. Possibilities of avoiding this drawback are to seek advice from the greatest possible number of eventual users, to compare with other similar inventories already completed and if necessary to request consultancies from forest management, logging, or forest economics specialists at the time when the inventory is being designed.

b) Another difficulty comes from the evolution of the purpose of the inventory. The aims defined during the preparation of the inventory may change during the course of the operation. This occurs, for instance, when the unit size of the blocks, for which the results are to be provided with a given precision, changes. This is also true for long programmes of forest inventory at a national level. There is no general course of action to overcome this difficulty; the only observation to be made is that the more flexible the initial design, the easier the transformation thereof. Moreover, every effort should be made to foresee some of these eventual modifications when designing the inventory.

122 Priority of objectives. Not all the objectives have the same importance. Some are very fundamental and can in themselves justify the whole inventory. The corresponding information has to be given in the required form or the operation will fail. The degree of precision of the information provided is also a most important requirement. On the other hand, it may be acceptable to fulfill a secondary objective only approximately (for instance, by accepting a lower precision in the corresponding information).

The priority of the objectives to be met has to be clearly assessed before designing an inventory. For instance, if the estimation of the area of a forest is more important than the estimation of its volume, the inventory design will strengthen the work of interpretation of remote sensing imagery and mapping and give less importance to tree measurements on imagery or in the field. Likewise, priority can be assessed among the

zones or the blocks of the region inventoried. As far as volume estimation is concerned, species do not have the same economic value, so the inventory will be designed in order to provide the results with a specific precision for the most important species: volumes of individual secondary species may be estimated less precisely, especially if they have a very low stocking density and are unevenly distributed.

123 Additional requirements. Forest inventories generally include a substantial amount of field work, which implies high expenditure and more or less difficult logistics. In particular the ratio:cost of accessibility to the sampling plots/cost of data recording is sometimes very high. The additional cost incurred by measuring and recording other parameters, not directly related to the purpose of the inventory, may prove insignificant. Under such conditions it may be desirable to take the opportunity offered by the inventory logistics to collect data of value to specialists not concerned with the primary purpose of the inventory (soil scientists, dendrologists, phytoecologists, etc.). This is all the more justified as a forest inventory often provides the most objective and exhaustive way of penetrating unknown and remote areas.

There is no general answer to this question, and each inventory operation is a special case. Many things have to be considered, among which we can quote (a) the cost of the collection of these additional data, and (b) the qualifications and training of the field staff for this additional work and the corresponding reliability and precision of the data collected.

Even if not explicitly required for the purpose of the inventory, some data have to be systematically collected, because they are known to be useful in any case. In tropical forest inventories these data are:

- logging parameters, i.e. slopes, soil bearing capacity, terrain obstacles, undergrowth, occurrence of swampy areas, etc.;
- complete enumeration of trees by species and diameter classes above a given minimum diameter (say 10 cm) in a sub-sample of the sampling plots, if only certain commercial species are to be inventoried in the main sample;
- enumeration of seedlings, saplings and poles of the most important species in a sub-sample of the sampling plots, for further regeneration and management studies.

Other data, although not of direct relevance to the purpose of a forest inventory, can easily be recorded either in the office (such as climatic data) or in the field (such as seed collection aspects for individual species, degree of dominance of the crowns, dates and periodicity of seed crops, etc.).

In any case the attitude of the inventory officer, when he is faced with requests concerning additional data, should be positive. Probably the most advantageous solution is to ask the respective specialists and researchers or some of their trained staff to use the inventory infrastructure and join the inventory staff in order to collect their own data. This solution would also be the most efficient as the data collected would be more reliable and the cost of the infrastructure shared between the two parties.

124 Most important specifications for the purpose of a forest inventory

1) Exact limits and size of the area to be inventoried (the existence of good recent topographic and land-use maps and/or remote sensing imagery will facilitate decisions at this stage);

ii) Divisions to be made within the area: this question is important as the intensity of the inventory depends on the size of the ultimate forest subdivision for which results are requested with a specific precision (these classifications exclude the stratification(s) performed to improve the precision of the results for the above units); these classifications may be:

- based on bioclimatic relationships (as for instance land capability classification);
- related to existing land-use and vegetation;
- related to forest management criteria such as:

  ownership and tenure
  administration
  physiography and accessibility
  protection (watershed catchment area)
  other management critera, e.g. logging compartments

- combination of two or several of the above classifications.

iii) Nature of the information required: Information may be pictorial (maps, mosaics, graphs and charts, etc.), descriptive (qualitative description of the forest types, for instance), or quantitative.

Regarding pictorial information some characteristics have to be defined such as scale and resolution (what the dimensions of the smallest patch of forest type to be shown on the map will be). This last characteristic pertains also to the precision of the required information.

As for quantitative results one may consider the following questions:

- do they correspond to a static and/or dynamic appraisal ? (i.e. at the time of the inventory only, or also concerning the evolution of the forest);
- are they means per unit area, e.g. per hectare (or, for some stands, per tree) or totals ?
- are the final results areas, numbers of trees, volumes, weights (for instance, in forest inventories for pulp production), prices (taking into account the unit prices of the products) ?

iv) Presentation of the information required: Once the type of information to be provided is know, as well as the desired precision, the method of eventual presentation of the results can be decided. The format of the final tables, for instance, will be drafted and shown to the users in order to get their agreement. This must be considered as an important item because clarity and reduction of the "access time" to the results are two important qualities of an inventory report. Moreover a dialogue between the users and the makers of the inventory at this stage, regarding the eventual presentation of the results, sometimes facilitates a clearer definition of the objectives by the users.

A set of table outlines for quantitative results concerning areas and volumes, considered as the basic minimum information to be presented by all FAO forest inventories, was designed during the meeting of forest inventory experts attached to UNDP/SF projects held in 1967 in Rome. The purpose of this exercise was to harmonize the presentation of the results of FAO operations (and thus facilitate in particular the periodic assessment of forest resources at national, regional or world-wide levels). These tables are presented in Chapter 6 of this Manual which deals with data recording and processing problems in forest inventory.

Complete standardization of the tables of results given by all forest inventories is probably not foreseeable in the near future. However, it would help considerably if the table outlines in Chapter 6 could be used as far as possible, with additional tables produced whenever necessary.

v) Precision of the information required: the precision of the results corresponding to the most important parameters must be determined prior to the inventory. For some other parameters, the precision required may not be determined exactly, but must not exceed a certain order of magnitude. Regarding precision, three important considerations have to be taken into account:

a) the total error of a sampling estimate has two components:

- one is the sampling error calculated from the values measured in the sampling units, which is related to "precision" in its statistically restricted sense;

- the second is the bias which may originate either from the sampling procedure, from the estimation procedure or from the measurement errors (for analysis of bias in sampling, see paragraph 24 of Chapter 3). Sometimes the bias may far exceed the sampling error[1/] which is, often and wrongly, the only one taken into account. When we speak about precision of an estimate in general, we must refer to the total error and not only to the sampling error. One must try to estimate the total error using in particular objective checking procedures, and must design the inventory to ensure that this total error is no more than the admissible error. This point is one of the most tricky problems and, unfortunately, one of the least studied in textbooks and inventory reports.

b) Required precision in all sampling designs must be given at a certain probability level. The meaning and the choice of a probability level is not always well conceived by the potential users of inventory results, although this has a considerable impact on the intensity of the inventory work. Whenever necessary, this point will have to be well clarified before designing the inventory.

c) Required precision must be referred to a given population, which may be the whole area inventoried or only subdivisions of it (administrative units, vegetation types, compartments, watershed catchments, logging blocks). The mean size of these divisions greatly influences the intensity of the inventory work.

It is desirable that each figure be given at least with its corresponding sampling error. Precision for many secondary results is frequently not estimated in order to reduce the cost of data processing. However, precision of certain figures may be very low, due to the high variability of the corresponding parameter. It is necessary to point out the expected low precision of these figures or to omit them altogether (for instance if the result is related to the volume of a species of very rare occurrence, it may be combined with the corresponding figure for other species so that the combined figure is reasonaly precise).

1/ Especially in complete (100% sample) inventories in which, by definition, sampling error is zero.

2 Outline for preparing inventory plans

The following outline is presented as an example of a format which can be used in preparing plans for a forest inventory. This example is given with the knowledge that there is no single outline which should be used at all times, since the outline will necessarily vary to fit the inventory under consideration. The important point is that a written plan should be prepared and all the topics shown below should be considered. Items mentioned in the previous sub-chapter are summarized under the heading "Purpose of the inventory".

I. Purpose of the inventory

a) General definition of the objectives in collaboration with the potential users of the results of the inventory.

b) Priority of objectives.

c) Additional requirements (to be discussed with interested specialists: soil scientists, ecologists, botanists, etc.).

d) Detailed specifications of the objectives:

- exact limits and size of the area to be inventoried
- divisions to be made within the area
- nature of the information required
- presentation of the information required
- precision of the information required

II. General information

a) Authority responsible for the inventory and other agencies collaborating.

b) Available information and data on the area to be inventoried from past surveys, reports, maps or remote sensing imagery on:

- general description of forest
- variability of parameters to be measured
- condition of terrain, accessibility, transport facilities

c) Resources available for carrying out the inventory.

III. Inventory design

a) Outline of inventory design to be used.

b) General description of the various phases.

i aerial surveys, interpretation of remote sensing imagery
ii mapping and area estimation procedures
iii complete tally or sampling methods for recording of forest characteristics
iv relationships to be used for expressing estimated quantitative data of stands, e.g. volume tables

IV. Measurement procedures

a) Description of design for both office and field work; in particular, size, shape, number and distribution of sampling units to meet required precision.

b) Procedures of interpretation of remote sensing imagery:

- detailed instructions on all techniques;
- ii staffing and description of duties;
- iii instruments;
- iv) forms and recording of observations

c) Field organization:

- i) crew organization and description of duties;
- ii) transportation procedures and directives;
- iii) camping instructions;
- iv) provisions for logistical support

d) Field procedures including detailed procedures on:

- i sampling unit location;
- ii establishment of sampling unit;
- iii measurements on sample unit;
- iv instruments and directives for use;
- v) tree and other plot measurements;
- vi) other field measurements such as growth, insect damage, mortality, soil and topographic conditions, seed collection aspects and information on non-productive roles of the forests;
- vii) design of forms and recording of observations

V. Compilation procedures

a) Detailed instructions on processing of data from imagery interpretation and field measurements:

- i) formulae for estimates of means totals and their sampling errors;
- ii) relationships to be used for converting imagery or field measurements to desired expressions of quantity; e.g. photo-volume tables, individual tree volume tables, etc.

b) Calculation and compilation methods:

- i) description of procedure, e.g. desk calculation, electronic computers, etc.
- ii) detailed description of all phases of calculation from raw data on original forms to final results (for electronic computation, description of inputs, programmes, and outputs).

VI. Final Report

a) Outline (note that the inventory plan, with some modifications, can serve as a basis for the final report).
b) Estimated time for preparation.
c) Responsibilities for preparation.
d) Method of reproduction.
e) Number of copies
f) Distribution.

CHAPTER III

BASIC SAMPLING TECHNIQUES

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BASIC SAMPLING TECHNIQUES

1. Introduction

11 Sampling in forest inventory

111 Sampling is a necessary technique used in most forest inventories for economic reasons. Populations to be inventoried, e.g. population of forest plot units, or population of trees for the assessment of volume tables or of defect, or for the estimation of mensuration parameters in plantations, are usually too large to be fully enumerated.

Several sampling procedures may be used in the same forest inventory in different parts of the operation. Their main, but not exclusive, use is for the estimation of the forest areas and of the mensuration parameters. In speaking about the sampling design of a forest inventory one generally refers to the disposition of the field samples.

Although other statistical techniques may be used in a forest inventory, an example of which is multivariable analysis - regression - for assessment of volume tables, this Manual will deal only with sampling techniques. Information on these other relevant statistical techniques will be found in statistical textbooks, some of which are listed in the bibliography.

112 Objectivity in sampling. Sampling must be objective in order not to introduce a subjective bias in the sampling estimates. A forest inventory using subjectively selected plots (for instance by selection based on the "experience" and a knowledge of the forest area of the designer) cannot give valid estimates as it is impossible to know the importance and the sign of bias and to determine the sampling error of them. Objectivity is not synonymous with unbiased estimates of the parameters. One can deliberately use a biased estimation provided that the bias is lower than a given limit. "Ratio estimation" is a biased type of estimation which proves very useful in many cases.

Nor is objectivity synonymous with randomness. Many systematic designs are objective and also give unbiased estimates, although in most cases a systematic layout cannot be assimilated to a random device. The only trouble with samples of this type is that their non-randomness prevents the user from applying the statistical sampling theory and getting unbiased estimates of the sampling errors.

113 Selection of the sampling design. Theoretically the most efficient sampling design is the one which provides the most precise estimates for a given cost, or which costs the least for a given precision of the estimates. Under the term "precision" one must consider not only sampling errors but also constant and variable biases (see paragraph 24 of this chapter). The evaluation of cost should also be the most comprehensive one. In many cases it is very difficult to perform a complete and precise study of efficiency and to find out the most efficient sampling design. Approximative calculations taking into acoount only sampling errors and basic cost figures point out the best sampling design according to this simplified procedure.

But the selection of the sampling design must not rely only on this partial calculation based on the sampling theory and available cost figures. The incidence of the measurement errors, which generally cannot be entered in the efficiency calculation, must be reduced to a minimum. This means that the tasks in which junior staff are involved - especially field work - must be easy and simple, as must be their control.

These requirements are very important and must be kept in mind when selecting the sampling designs(s) of the inventory. All possible measures must be taken to improve the reliability of the data, even if this leads to a slight increase of the sampling error and/or total costs.

114 Relative importance of the sampling techniques in forest inventory.

The last paragraph shows that the sampling methodology has to be considered together with practical matters in order to make the inventory results precise and reliable.

Furthermore, photointerpretation and forest mensuration techniques which are not - or only partly - related to the sampling theory are fundamental in forest inventory, for instance forest classification, estimation of volumes of standing trees, defect assessment, etc. Thus sampling techniques can be considered as only one among other tools of forest inventory, and their importance must not be overestimated. Forestry officers involved in inventory work must have a basic knowledge in this field - and that is why one complete chapter in this Manual is devoted to sampling techniques. Reliability and validity of the inventory results are not only a question of sampling procedure; forest inventories using sophisticated sampling designs may give unreliable and useless results while simple sampling designs may be a characteristic of good and effective forest inventory operations.

12 Outline of the chapter

The first priority is to define the most useful statistical concepts and describe how they have to be used in the field of forest sampling. Then the basic mathematical and statistical techniques will be given which are commonly used in sampling designs, such as normal distribution hypothesis, variance of compound values, ratio estimation and optimization of a design. Finally some of the most common classical sampling designs used in forest inventory will be presented with the corresponding formulas for the estimation of the mean value of a given parameter per unit and its sampling error.

2 Statistical concepts(1)

21 Population

A population is an aggregate of units (or elements) of the same nature, the definition of which has to be clearly expressed. For instance, a forest is considered as the aggregate of a finite number of contiguous plots of equal or unequal size, or as the aggregate of all the living trees within the forest (this definition being useful in the inventory of plantations); a mapped zone is considered as the aggregate of an infinite number of points, when sampling by dot counts is used for estimating its area.

It is important to consider the two following points:

- the population may have a finite or infinite number of units and in both cases the definition of a unit of the population must be sufficiently precise to know without ambiguity if a given unit belongs or not to the population;

- the units are of the same nature but are not necessarily the same size: for instance each unit may be a forest compartment, the whole population being a large forested area; one unit may also be a variable part (or subplot) of a plot area, if the plot areas are distributed in a partially forested area (in this latter case, the population is the forested part of the area).

(1) The term parameter will be used in the manual to indicate any variate of a sampled population which is to be estimated by the sampling procedure.

The following remarks can be made regarding the concept of population:

(i) The term "population" has a statistical meaning which is more definite than in the common language. For instance, there is only one population of Italian people living in Italy; but it is useful in demographic studies of this population, to define various statistical populations which have the same overall size, but the units of which have not the same attributes: the unit of one of these statistical populations may be the family, another statistical population could be made up of groups of people living in a specific building, etc.

(ii) Sometimes the term population is referred to the aggregate of the values of one of the parameters to be estimated by the inventory over all the units and not to the aggregate of the units themselves; we think that, unless otherwise specified, population must be understood in the sense of aggregate of the units as sampling is done among the units themselves and not among the values of the parameter.

(iii) It may happen that the aggregate of all the units cannot correspond to the whole population. For instance, if the units are circular plots, there is no way of aggregating them in order to form the whole population. Although the use of circular plots is common, this problem does not seem to have been dealt with. For small sampling intensities and a relatively small size of the plots, this problem can be considered of minor importance and formulas will be used as if there were a possible aggregation of the units.

(iv) The population to be sampled must be clearly defined, before any sampling procedure is designed. For instance, if it is an area, the limits of the area must be known. Two considerations are related to this statement:

(a) Sampling theory does not provide any way to estimate a parameter over a population if one has obtained an estimate of the same parameter by sampling only in a part of the population, or in a different population.

(b) A distinction must be made between the "overall population" and the "population of reference". Let us take an example to clarify this point. Being given a high tropical forest of 100 000 ha which is the "overall population" to be inventoried, one may expect a precise estimate of the mean parameters per area unit for this whole population or for subdivisions of it ("blocks", "compartments", "management units", etc.) which we will call "populations of reference". Thus there will be various inventory options for the same "overall population" and for the same precision on a given parameter, according to whether this knowledge is requested over the whole population or over sub-divisions of it ("population of reference"). The definition of the "population of reference" is of course the one which is important from a statistical point of view. This remark points out the need to state clearly at which level are the results requested in a forest inventory. Sometimes decision makers ask for the survey of a given forest area without defining the size of the reference unit areas for which they need a precise estimate of the important parameters. They have to define it, because the range of the sampling intensities of the forest inventory is wide, from light intensity inventories if they are interested in an overall knowledge, to very high intensities if the useful sub-divisions are very small.

22 Distribution

221 Different kinds of values of parameters in one unit of a population

A given parameter has one value in each unit of a population. For instance, let us assume that the parameter is the "number of stems of Shorea albida of more than 10 cm reference diameter per hectare", that the population is a forest area, the units of which are 0.1 ha plots. If in one unit there are two Shorea albida with a reference diameter of more than 10 cm, the corresponding value of the parameter for this unit is 20. This parameter has discrete values, because the corresponding items (stems) are not divisible.

If, in this population, we consider the parameter "gross volume of the boles of Shorea albida with a reference diameter more than 10 cm per hectare" - the volume of a tree being related to its reference diameter and height through a volume table - the values of this parameter corresponding to the various units will be continuous, because the values which can be taken by the parameter are close to one another according to the many possible combinations of numbers of trees in a plot with various possible reference diameters and heights.

The value in a unit of the first parameter is determined through a count while that of the second is obtained from a count and measurements of specific characteristics of the trees which are used to estimate volumes through a regression equation (volume table).

Very often a parameter of a population is estimated by assigning each sampling unit to a given class. Let us suppose we want to estimate from a certain number of photo-interpretation plots of equal size the proportion (in area) of a given forest type within a forest area (population). To each plot we will assign a variable, the value of which for the plot is:

0 if the plot is not, or only for a minor part, in the forest type;
1 if the plot is entirely, or for a major part, in the forest type.

The mean value of this variable over all the sampling plots (which will be a positive value between 0 and 1) is an estimate of the proportion in area of this forest type within the whole forested area.

If we consider all the forest types of this forest area, it is easy to verify that the sum of the related estimated proportions is equal to 1 (and that the variance of this sum is equal to 0, which is an expected result as, whatever the sample, the sum of these estimated means is constant and equal to 1).

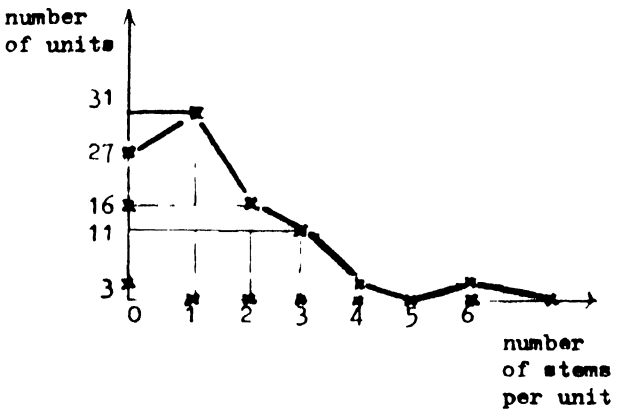
Most of the following considerations in this chapter apply equally to sampling for estimation of parameters resulting from measurement, count or assignment. The way of calculating the variance is the same for continuous parameters and variates (0,1) but the resulting formulae are different, for they can be simplified in the case of the variables (0,1) used for estimation of proportions.

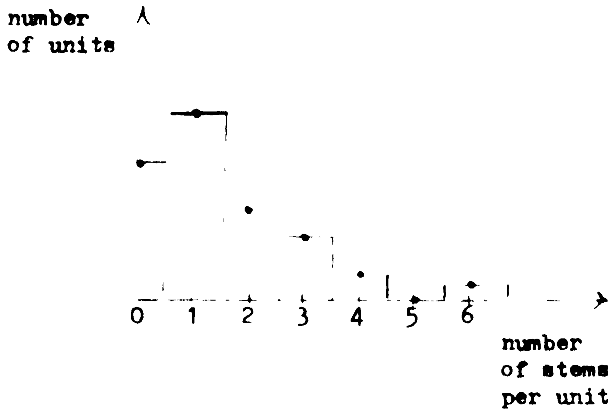
222 Distribution of the values of a parameter over a whole population

The value of the parameter to estimate in all the units of the population are distributed in a certain way. Let us assume the parameter can take only discrete values in each unit of the population, e.g. when it is the number of stems of a given species.

If we consider all the units of the population, we can represent the population by a chart of points (fig. 1) the coordinates of which are:

- on the x-axis the number of stems of this species in one unit;
- on the y-axis the number of units of the population having a given number of stems of this species (or <u>frequency</u>)





<u>Fig. 1</u>

Very often such a graph is presented in the form of a <u>histogram</u>: for each discrete value of the parameter there will be a rectangle based on the corresponding ordinate, the height of which is given by the frequency related to this ordinate.

In the case of a continuous parameter, we can gather the information by classes of parameter value. In this case we will also get a histogram; the smaller the classes, the narrower and more numerous will be the rectangles.

We can imagine that if the width of the classes (and of the corresponding rectangles) decreases, the representative points will be closer to each other and their y-ordinates will also decrease. The distribution can then be represented by a curve which joins the points (<u>distribution curve</u>).

One distribution for continuous variables is very useful in sampling techniques. It is the <u>normal distribution</u> with a curve symmetrical in relation to the axis of x-ordinate equal to the mean value of the parameter. We will see that if the estimates of the values of a mean obtained from all samples of the same type are distributed "normally" around the expected value of this mean, it is possible to give the sampling error of this estimate at a given probability level.

223 Characteristics of central value and dispersion of the distribution

Two characteristics of the distribution of the values of a parameter over a whole population are of particular interest for its estimation. They are (assuming the population is finite):

a) the mean value of the parameter per unit. If:

x is the parameter

x_i its value in the i^{th} unit

N the total number of units in the population

the mean $\bar{X}$ of the parameter per unit will be equal to:

$$\bar{X} = \frac{\sum_{i=1}^{N} x_i}{N}$$

We can also write $$\bar{X} = \sum_{i'} p_{i'} x_{i'} = E(x)$$

where $p_{i'}$ is the probability for the parameter x to be equal to $x_{i'}$, the sum $\sum_{i'}$ being extended to all the possible values $x_{i'}$ of the units of the whole population;

$\bar{X}$ is also called the expected value of the parameter x in the population which is written $E(x)$;

the total of the parameter over the whole population is the sum of the values of the parameter for all the units:

$$X = \sum_{i=1}^{N} x_i = N\bar{X}$$

b) the variance of the value of the parameter in a given unit is

$$\sigma_X^2 = \frac{\sum_{i=1}^{N} (x_i - \bar{X})^2}{N}$$

This characteristic is a measure of the dispersion of the values of the parameter around the mean value of the parameter.

We can write also: $$\sigma_X^2 = \sum_{i'} p_{i'} (x_{i'} - \bar{X})^2 = \sum_{i'} p_{i'} [x_{i'} - E(x)]^2$$

($p_{i'}$, $x_{i'}$ and $\sum_{i'}$ having the same meaning as above)

The variance is also the expected value of the square of the deviations between the values of the parameter in the population and the mean $\bar{X}$, and is written:

$$\sigma_X^2 = E[x - E(x)]^2$$

The square root of the variance is the standard deviation which is:

$$\sigma_X = \sqrt{\frac{\sum_{i=1}^{N}(x_i - \bar{X})^2}{N}}$$

The standard deviation is not a pure number and depends on the system of measuring units.

The coefficient of variation $C_v = \frac{\sigma_X}{\bar{X}}$ is a pure number and is very useful to characterize the variability of a parameter over the whole population.

If two parameters are to be estimated in the same population x and y, we can define a cross measure of variation, called covariance:

$$\sigma_{XY} = cov(x,y) = \frac{\sum_{i=1}^{N}(x_i - \bar{X})(y_i - \bar{Y})}{N}$$

y_i and $\bar{Y}$ being respectively the value of the parameter y in the i^{th} unit and the mean value of y over the whole population.

The correlation coefficient ρ between y and x in the population defined by the equation:

$$\rho = \frac{cov(x,y)}{\sigma_X \cdot \sigma_Y}$$

will characterise the cross variation of the two parameters y and x in the population (ρ is a pure number whereas σ_{XY} depends on the units chosen for estimating the parameters x and y).

224 Value of a parameter per area unit in one unit of the population

As we have seen from the example in paragraph 221 there is one value of the parameter "number of trees of a given species per hectare" in each unit of a forest area. This parameter has a mean value over all the units of the whole population, which is the mean number of stems per hectare of this species. In order to avoid confusion we recommend using the complete expression "mean value per area unit" to denote the mean value of the parameter per unit (of the population) referred to the area unit. If all the units of the population have the same area (size), the mean value per area unit is equal also to the mean of the values per area unit in all the units of the population.

23 Sampling

As in most cases the population to be studied is too large to be fully enumerated and/or measured, it is feasible to have this work done only on a selection of units from the whole population. Such a selection is called sampling, the selected elements are the sampling units, and the whole set of sampling units is the sample. Provided given procedures of selection are followed, sampling techniques are useful:

i) to get an estimate of the true values of the mean and of the total, over the whole population, for a given parameter, from the values of this parameter in the sampling units;

ii) to get an estimate of the sampling error (or of the precision or of the confidence limits) at a given probability level, for the estimated mean or total given by the sample.

Estimating the sampling error is sometimes very difficult and, in certain cases, the formulae used are only approximate. This calls for the use of simple sampling designs whenever possible.

Some concepts have to be stated clearly in relation to sampling.

231 Size of sample

Given a size unit which may be an element or an individual (such as a tree), or a measurement unit (such as a hectare) the size of a given population and any of its units must be measurable. The units of the population may be of different size: this is the case where a forest area has curvilinear limits, the units of which are strips of equal width but of unequal length, the size being expressed, as in many forest inventories, in terms of area.

The size of sample is the sum of the sizes of the sampling units.

The sampling intensity (or sampling fraction) is equal to the ratio of the size of the sample to the total size of the population. If the population has N units of equal size and if the sample has been made up by selection of n different sampling units, then the sampling fraction f is equal to:

$$f = \frac{n}{N}$$

In this case (equal units) n can be said to be the size of sample.

A difficulty arises when the unit is a point and therefore has no dimensions. This case occurs when one estimates the proportion of area in a given forest type over the whole inventoried area, using a dot grid laid on a forest map or when the forester is using a point sampling method (see paragraph 422.2). The sampling fraction in the first case will be said to be negligible, whilst in the second case the sampling intensity will vary according to the relevant characteristic of the trees (basal area, diameter, square of height, height): if it is the horizontal point sampling method, the sampling intensity of trees of 56 cm diameter will be exactly equal to four times the sampling intensity of trees of 28 cm diameter. Generally, even for the biggest or highest trees this sampling fraction is small and can be considered negligible in the sampling error calculation.

232 Precision and sampling error. The estimate of the mean or the total of a parameter given by a sample is generally different from the true corresponding value over the whole population. The sample will be more valuable as the estimate becomes more accurate, which means that the estimate is closer to the true value. This accuracy cannot be expressed in an absolute way as, in the following sentence, "the accuracy of the estimate of the mean of this parameter over the whole population is ± 3%". It can, however, be expressed in a probable way, and is called precision or sampling error. In the former example precision is stated as being equal to ±3% at a given probability level. If we say "at 0.95 probability level", this will indicate that for 95% of similar samples drawn from the same population the true mean will be within the ±3% interval from the estimated mean given by every sample. It is also expressed by saying that the probability of the true mean being within the ±3% confidence interval is 0.95, or, which is equivalent, that the probability of the true mean being outside this interval is 0.05. In this case, the 0.05 measures the risk we are prepared to accept of being wrong when we say that the sampling error is ±3% at 0.95 probability level. Whatever the sampling, the sampling error would be meaningless and infinite (or the precision will be null) if one attempted to express it at a 100% probability level.

The selection of a probability level to which the sampling error of an estimate corresponds must be made by the user(s) of the forest inventory. It is not enough to request a given precision; the probability level must be specified. A precision equal to ± 10% at 0.95 probability level ("19 out of 20") is better than the same precision at 0,68 probability level ("2 out of 3"). We will see (paragraph 31) that in many cases the second precision is equivalent to ± 20% at 0,95 probability level. Any sampling precision given without a reference to a probability level is meaningless.

The most frequently used probability levels in sampling techniques are 0.95 and 0.68 (the reason will be given in paragraph 31). These two probability levels are sometimes referred to respectively as 0.05 and 0.32.

Sampling errors are expressed not only in percentage of the estimated result but also in the corresponding measuring units. In this case it is also possible to express the "confidence limits" at a given probability level in these units. For instance, if the sampling estimate of a mean volume per hectare is 40.0 m^3 and the sampling error ± 5.0% at 0.95 probability level, the confidence limits will be:

$40.0m^3 - 0.05 \times 40.0m^3 = 38.0m^3$ = lower confidence limit at 0.95 probability level

$40.0m^3 + 0.05 \times 40.0m^3 = 42.0m^3$ = upper confidence limit at 0.95 probability level

the confidence interval being (38.0 - 42.0).

The probability for the true value to be less than the lower confidence limit is equal to the probability for it to be more than the upper confidence limit. In case of a 0.95 probability level, this means that the true value has a 0.025 probability to be less than the lower confidence limit and a 0.025 probability to be more than the upper confidence limit.

It may be useful to refer the estimate to only one of the confidence limits. Where the estimate is a mean exploitable volume per hectare in a forest, we are more interested in the lowest volume to be expected at a given probability level. In this case the lower confidence limit at the probability level is called the "reliable minimum estimate" (RME). If the probability level corresponding to this confidence limit is 0.95 (or 0.05), the reference probability level for this RMA will be 0.975 (or 0.025). This means that this RME will have 0.975 probability to be exceeded by the true value, or 0.025 probability to be higher than this true value.

In a given forest inventory, several sampling designs may be used, one for the interpretation of the remote sensing imagery (area estimation), one for the field work (estimation of number of stems), a third for the calculation of volume (using a sample of completely measured trees for elaboration of volume tables), etc., and each will have a different sampling error which may be related to the others. The total sampling error is a combination of these partial sampling errors and is not the mere addition of them. In most cases, it is difficult if not impossible to estimate it properly. This calls, once more, for the use of simple inventory designs which provide the user with reliable results with the requested precision.

233 Other concepts. The selection of the units of the sample (or sampling in the narrow sense of this word) must be made at random: this is a fundamental requirement for the application of the sampling theory. For instance, there is no completely valid method of assessing the sampling error of an estimate given by a systematic sampling design, because the basic requirement of randomness is generally lacking. This does not mean that the estimate itself is not valid (see paragraph 422 of this chapter).

Probability of selection in sampling

Sampling theory can be applied in principle only if the composition and probability of selection of all possible samples of a given sampling design from the whole population is known. In practice it is sufficient to know the probability of inclusion for the units themselves. The probability of selection of a unit is the chance that it has of being drawn for inclusion in a sample during the constitution of the sample. This probability is expressed as a figure of less than one; one, or certainty, being the sum of the sampling probabilities of all the units of the population. The probability of selecting a given type of sample of n units can be assessed from the probabilities of inclusion of each sampling unit in the sample.

Examples (sampling with replacement):

a) In a simple random sampling of a population of N units, in which all units are selected with equal probability, the probability of selection of the unit i is equal to

$$p_i = \frac{1}{N} \quad \text{with} \quad \sum_{i=1}^{N} p_i = N \times \frac{1}{N} = 1$$

b) In a sampling with probability proportional to the size M_i of each unit (called PPS sampling) we will have:

$$p_i = \frac{M_i}{M_o} \quad \text{with} \quad M_o = \sum_{i=1}^{N} M_i$$ being the size of the whole population.

Replacement

When the first unit of a sample has been selected, two alternatives are possible:

- to draw the second unit from the whole population including the first sampling unit (sampling with replacement);
- or to draw the second unit from the population which does not include the first sampling unit (sampling without replacement)

(the procedure used being repeated after each drawing of a sampling unit, until the full ple is constituted).

In sampling with replacement the same units may be drawn and included in the sample more than once.

Most of the formulae used in practice are valid only for sampling with replacement. However, almost all samples are drawn without replacement. This approximation is acceptable provided that the number of sampling units is relatively small in proportion to the total number of units in the population (or the stratum if it is a stratified sampling see paragraph 411.4).

24 Bias and measurement errors

241 **Bias.** The concept of expected value (see paragraph 223 of this chapter) can be applied to the estimate given by a sample. If $\hat{\mu}$ is the estimate of a parameter given by a certain type of sample, and $\hat{\mu}_j$ the estimate given by the sample j from this type of sample, the expected value of $\hat{\mu}$ is:

$$E(\hat{\mu}) = \sum_j \pi_j \hat{\mu}_j$$

where π_j is the probability of the sample j ($\sum_j \pi_j = 1$) and the sum $\sum_j$ is extended to all the samples of the same type.

The estimate $\hat{\mu}_j$ from a sample of this type is unbiased if its expected value $E(\hat{\mu})$ is equal to the actual value μ of the parameter over the whole population: $E(\hat{\mu}) = \mu$.

If it is not so, the estimate is biased and the bias is equal to the difference between the expected value of the estimate and the actual value of the parameter of the whole population.

In this case: $E(\hat{\mu}) = m \neq \mu$ with the bias: $B = m - \mu$

The concept of bias relates also to other estimates given by a sample and in particular to the estimate of the sampling error.

(1) Let us suppose that the characteristic μ is the mean basal area per hectare $\bar{g}$ of all trees of more than 10 cm diameter in a given plantation, and consider that we estimate $\bar{g}$ from a certain type of a sample of trees. Let us assume that the section at breast height of all the trees is circular, but that the tape used for measuring the diameters has shrunk and says 21 cm when the diameter is actually 20 cm and that there is no other possible measurement error.

Each tree will be given a basal area g' equal to $\left(\frac{21}{20}\right)^2 g = 1{,}1025\ g$, g being its actual basal area. The expected value $E(\hat{g})$ of the mean basal area per hectare over all the samples of that type will be: $\bar{g}' = 1{,}1025\ \bar{g}$.

Here the bias is equal to:

$$B = \bar{g}' - \bar{g} = \bar{g}\,(1{,}1025 - 1) = 0{,}1025\ \bar{g}$$

(2) Let us assume that the characteristic μ is still the mean basal area per hectare g of all trees more than 10 cm diameter in a given forest area. The sample is constituted of n sampling units of unequal size sampled with equal probability. There is no measurement error.

A commonly used estimate for g is:

$$g' = \frac{\sum_{i=1}^{n} g_i}{\sum_{i=1}^{n} s_i}$$

where: i is the reference number of a sampling unit

$\sum_{i=1}^{n}$ is the sum extended to the n sampling units of the sample

g_i is the total basal area in the sampling unit i

s_i is the area of the sampling unit i

It is called a ratio estimate and is sometimes used in forest sampling because it is not always possible to have sampling units of the same size.

This estimate is biased and the bias has an order of magnitude of $\frac{1}{n}$

(3) As has already been stated (paragraph 112 of this chapter), a bias may result from an incorrect sampling design. For instance this occurs when the sample is constituted of the so-called "representative" sampling units chosen by the forester on the basis of his "experience" and knowledge. Another case of bias due to the sampling may arise when some parts of the population to be sampled are not taken into account in the sampling design: this occurs in forest inventory when, for instance, sampling units falling in less accessible areas are systematically replaced by more convenient units.

These three examples show that bias may have three origins:

- measurement errors;
- estimation of the parameter from the sample;
- sampling procedure.

Bias due to the sampling procedure is not always recognized and practically impossible to evaluate. An estimate of the bias can be provided in some biased estimation procedures.

242 Measurement errors. The measurement errors can be split into three components:

- a constant bias over the whole population (as for instance in the case of measurements by a device in which the zero graduation does not correspond to the zero measure);
- a variable component, in relation to the sampling unit which may be correlated to the exact value of the measured parameter in the corresponding unit (for instance, as in the case described in the first example of the former paragraph: the variable component of the bias on the diameter measurement is in this case equal to 5% of the diameter);

- a "fluctuating" component in a given sampling unit of mean 0 (its variance could be estimated if several measurements of the same parameter were taken in the given sampling unit).

The measurement error affects the reliability both of the estimate of the mean (the expected value of which is different from the true value of the mean) and of the estimate of the sampling error. Assuming that the sampling design is correct and that the exact sampling error calculation is done, the resulting estimate of the sampling error is a biased estimate of the true sampling error.

3 Basic mathematical and statistical techniques

31 Principles of sampling error estimation

311 Introduction. Let us call μ the true value of a mean of a parameter over the whole population, $\hat{\mu}$ the estimate of this value given by a certain type of sample and $\hat{\mu}_j$ the estimate given by the sample j of this type. If we take all the samples of this type, the corresponding estimates will be distributed in a certain way. The distribution of the estimates $\hat{\mu}_j$ will have the following characteristics:

(a) characteristic of central value (mean of the estimate $\hat{\mu}_j$)

$$m = E(\hat{\mu}) = \sum_j \pi_j \hat{\mu}_j$$

where: π_j stands for the probability of drawing the sample j ($\sum_j \pi_j = 1$)

E stands for "expected value" (see paragraph 223)

and $\sum_j$ is extended to all the samples of this type.

If all the samples have the same probability of being drawn ($\pi_j = \pi = \frac{1}{M}$ where M is the total number possible of samples of a same type), we will have:

$$m = E(\hat{\mu}) = \frac{\sum_j \hat{\mu}_j}{M}$$

We have seen (paragraph 241) that if $\hat{\mu}$ is unbiased we will have: $m = \mu$

(b) Characteristic of dispersion (variance of the estimate)

$$\sigma^2(\hat{\mu}) = E[\hat{\mu} - E(\hat{\mu})]^2 = \sum_j \pi_j [\hat{\mu}_j - m]^2$$

(with the same annotations)

If all the samples have the same probability of being drawn ($\pi_j = \pi = \frac{1}{M}$) we will have:

$$\sigma^2(\hat{\mu}) = \frac{\sum_j (\hat{\mu}_j - m)^2}{M}$$

Attention is called to the fact that the distribution which is dealt with here is the distribution of the estimates $\hat{\mu}_j$ of the mean value of a parameter over the whole population given by all the samples of a certain type, but is not the distribution of the values of this parameter over this population.

Example: Let us consider a forest stand (population) of N equal units of 0.25 hectare. As a sample, we select at random with equal probability and without replacement n ($n < N$) units ("sampling units") where we enumerate the number y of stems of a given species with a reference diameter more than 10 cm (this is the parameter).

The total number of possible samples of that type is equal to:

$$M = {}_N C_n = \frac{N!}{n!\,(N-n)!} \qquad (1)$$

which is the total number of distinct combinations of n different units from the total number N of the population units. All these samples constitute a population of ${}_N C_n$ elements. Each different sample has the same probability $\Pi_j = \Pi = \frac{1}{M}$ of being selected (they have an equal chance of being drawn, which can be calculated from the probabilities of selection of their n successive units).

The estimate from the sample j of the mean value (per unit) of y is:

$$\hat{\mu}_j = \bar{y}_j = \frac{\sum_i y_i}{n}$$

where the sum $\sum_i$ is extended to the n units i of the sample j.

(a) There are M possible estimates $\bar{y}_j$ and the expected value of $\bar{y}_j$ is:

$$m = E(\bar{y}_j) = \sum_j \Pi_j \bar{y}_j = \frac{\sum_j \bar{y}_j}{M}$$

the sum $\sum_j$ being extended to the M samples j (all the samples of that type).

If there is no bias due to enumeration or measurement errors, it is easy to prove that for this type of sampling, the expected value of $\bar{y}_j$, m, is equal to the true value $\bar{Y}$ of the mean value per unit of the parameter y (see paragraph 241).

Thus $\bar{y}_j$ is an unbiased estimate of $\bar{Y}$ and this type of sampling, which is called simple (or unrestricted) random sampling, is an unbiased sampling design.

$\hat{Y}_j = N\bar{y}_j$ is likewise an unbiased estimate of the total Y of the parameter over the whole population.

[1] N! means the product of the first N numbers: $N! = 1 \times 2 \times 3 \times 4 \times \ldots \times (N-1) \times N$.

(b) The variance of the estimate $\bar{y}_j$ (i.e. the characteristic of dispersion of the values $\bar{y}_j$ for the M possible samples of that type) is:

$$V(\bar{y}_j) = E[\bar{y}_j - E(\bar{y}_j)]^2 = \frac{1}{M}\sum_j(\bar{y}_j - \bar{Y})^2$$

the sum $\sum_j$ being extended to the M possible samples.

Sampling theory shows that $V(\bar{y}_j)$ for simple random sampling is equal to:

$$V(\bar{y}_j) = \frac{\sigma^2}{n}\left(1 - \frac{n}{N}\right)$$

where σ^2 stands for the variance of the values of the parameter over the whole population of N units.

The sampling error at probability level 0.95 on $\bar{y}_j$ is equal to:

$$e_0(\bar{y}_j) = \pm 1{,}96\sqrt{V(\bar{y}_j)} = \pm 1{,}96\frac{\sigma}{\sqrt{n}}\sqrt{1 - \frac{n}{N}}$$

provided that n is large enough.

$\frac{\sigma}{\sqrt{n}}\sqrt{1 - \frac{n}{N}}$ is called the standard error and corresponds, in case the normal distribution hypothesis is verified, to the sampling error at probability level 0,68 (see paragraph 312.1)

It is shown that an unbiased estimate of this sampling error from the sample (at probability level 0,95) is:

$$e(\bar{y}_j) = \pm 1{,}96\frac{s}{\sqrt{n}}\sqrt{1 - \frac{n}{N}}$$

where $s^2 = \frac{\sum_i(y_i - \bar{y}_j)^2}{n - 1}$ is an unbiased estimate of σ^2 from the sample

(the sum $\sum_i$ being extended to the n units i of the sample).

Similarly an unbiased estimate of the standard error (at probability level 0,68) is:

$$s(\bar{y}_j) = \pm\frac{s}{\sqrt{n}}\sqrt{1 - \frac{n}{N}}$$

This example shows that sampling theory gives, for a given sampling design, the following estimates:

- estimates of the true mean and total of the parameter for the whole population;

- estimate of the sampling error on these estimates at a given probability level.

Even if there is no bias due to the sampling design or to measurement operations, biased estimates may be preferred for the sake of convenience or simplicity in the calculations. In these cases care should be taken to keep the bias as low as possible.

It should be kept in mind, as has already been pointed out, that we cannot have the true values, but only estimates, of both the mean (or total) of the parameter and the sampling error. Generally speaking, good (unbiased or biased with a very small bias) estimates of means and totals are not difficult to determine. Acceptable sampling error estimates (on these estimates) are more difficult to calculate. The following paragraphs give some basic techniques used for the estimation of the sampling error.

312 Estimation of the sampling error on $\hat{\mu}_j$ from its variance. Normal distribution hypothesis. As has been seen in the case of simple random sampling, sampling theory gives an unbiased estimate of the variance of the estimate $\hat{\mu}_j$, provided that some requirements are observed (random selection, sampling over the whole population and not only over a part of it, etc.).

The problem now is to estimate the sampling error at a given probability level from the estimate of this variance, which is again the characteristic of dispersion of the distribution of all possible estimates $\hat{\mu}_j$ (the characteristic of central value being m, equal to the true value μ of the parameter over the whole population, if there is no bias in the estimation).

312.1 Simple random sampling

In this type of sampling we will assume that the distribution of all possible $\hat{\mu}_j$ corresponding to all samples of the same size n (which is not the distribution of the parameter over the population) is a normal distribution. This assumption is approximately verified when the number n of sampling units is large enough: it is usually agreed that normal distribution of $\hat{\mu}_j$ is obtained when $n \geqslant 30$ (1), whatever the distribution of the sampled population. The sampling error on $\hat{\mu}_j$ at the probability level u is proportional to the square root of its variance:

$$e_u(\hat{\mu}_j) = \pm t_u \sqrt{V(\hat{\mu}_j)}$$

The square root of the variance $V(\hat{\mu}_j)$ is called the standard error.

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(1) This agreement of course is somewhat arbitrary. For instance, if the sampling units are equal fixed-size plots of forest area and the parameter is the "number of stems of a given species more than 10 cm diameter", the estimate $\hat{\mu}_j$ of the mean value per unit of this parameter may have a more or less normal distribution when evaluated from only fifteen 0.4 ha sampling units, while the distribution of $\hat{\mu}_j$ cannot be considered normal when the sample is constituted of sixty 0.1 ha plots. With this reservation in mind, the figure 30 may be considered as a good order of magnitude of the minimum size of a sample in ascertaining whether the distribution of $\hat{\mu}_j$ is a normal distribution.

The average values of t_u corresponding to different probability levels for samples with $n \geqslant 30$ are given in the following table:

Probability level u	"Risk" of error α_u	$e_u(\hat{\mu}_j) / \sqrt{V(\hat{\mu}_j)}$ t_u
0,50	1 in 2	0,68
0,68	1 in 3	1,00
0,90	1 in 10	1,64
0,95	1 in 20	2,00
0,99	1 in 100	2,68

For other t_u values corresponding to other probability levels and specific values of n, one has to refer to the Student's table and the table of normal distribution.

The two most useful results, when $n \geqslant 30$, are:

- at a probability level 0,68 ("one chance in three of being wrong") the sampling error in $\hat{\mu}_j$ is equal to the square root of its variance $\sqrt{V(\hat{\mu}_j)}$, i.e. the standard error;

- at a probability level 0,95 ("one chance in twenty of being wrong") the sampling error in $\hat{\mu}_j$ is approximately twice the square root of the variance.

When $n < 30$ (number of sampling units in the sample less than 30), the assumption of normal distribution of $\hat{\mu}_j$ is no longer acceptable. There is generally no way of obtaining the sampling error from the variance of the estimate $\hat{\mu}_j$, due to the effect of the inaccuracy of the estimate of the variance from small samples. However, if we can consider that the values of the parameter are more or less normally distributed in the population, then we will still have the following relation between $e_u(\hat{\mu}_j)$ and $V(\hat{\mu}_j)$,

$$e_u(\hat{\mu}_j) = \pm t_u \sqrt{V(\hat{\mu}_j)}$$

the t_u values being taken from the Student's table.

This table is a two-entry table, one corresponding to the probability level, the other to the number of "degrees of freedom". This last concept is not dealt with in this manual. It is enough to know that in the simple random sampling, and in many other classical designs, the number of degrees of freedom is equal to $n-1$, where n is the number of sampling units in the whole population (or in a stratum in stratified sampling).

The following table is an excerpt from the table of Student's t for selected probability levels and sizes of sample:

Probability level u	Number of degrees of freedom						
	1	4	9	14	19	24	29
	n = 2	n = 5	n = 10	n = 15	n = 20	n = 25	n = 30
0.50	1.00	0.74	0.70	0.69	0.69	0.69	0.68
0.68	1.80	1.14	1.05	1.03	1.01	1.01	1.00
0.90	6.31	2.13	1.83	1.76	1.73	1.71	1.70
0.95	12.71	2.78	2.26	2.14	2.09	2.06	2.05
0.99	63.66	4.60	3.25	2.98	2.86	2.80	2.76

These t-values can be used, in the case of small samples ($n < 30$), only if the distribution of the parameter values over the population is roughly normal.

312.2 Other sampling designs

Simple random sampling is only one of a very large number of possible designs. In many forest inventories these other sampling designs have to be used and there is no simple answer as to whether the distribution of $\hat{\mu}_j$ can be considered as a normal distribution or not. The "normal approximation" will be more verified as the number n of sampling units becomes larger, the desirable minimum value of n depending on the distribution of the parameter over the whole population, and of course on the type of the estimate $\hat{\mu}_j$, itself a function of the type of sampling. The "normal approximation" is generally accepted, but one must always check if this is reasonable. The table of normal distribution will be used as indicated in the first part of paragraph 3121. It may be desirable in some cases to stratify the population into several sub-populations ("strata"), within each of which the distribution of the estimates $\hat{\mu}_j$ may be considered more "regular" and closer to the normal distribution.

32 Variance of compound values

321 Introduction. Let us consider a random value y, which may be the value of a parameter in one unit of a given population, or the estimate of the mean value per unit of a parameter over a population from a sample j of a certain type. This random value may be estimated, not directly from measurements within the sampling units, but through other random values which are themselves directly measured within the sample or already estimated from the sample.

Examples:- An unbiased estimate of the mean value per unit of a measurable parameter (e.g. basal area per unit, taking into account all trees more than 10 cm diameter over bark) in a simple random sample is:

$$\bar{y} = \frac{\sum_i y_i}{n} = \frac{y_1 + y_2 + \dots + y_n}{n} \qquad (1)$$

where i refers to all the n units of the sample.

The estimate $\bar{y}$ is a function of the random values y_i which are directly measured in the sample.

-An unbiased estimate of the mean value per unit of the same parameter y for the whole (population) of two stands (sub-populations or strata) sampled independently, is:

$$\bar{y} = \frac{S_1}{S}\bar{y}_1 + \frac{S_2}{S}\bar{y}_2 \qquad (2)$$

where S_i and $\bar{y}_i$ correspond respectively to the total area of the i^{th} stand and the estimate of the mean per unit in this stand (i = 1 or 2), while S is the sum of the S = $S_1 + S_2$.

The estimate $\bar{y}$ here is a function of the two estimates $\bar{y}_1$ and $\bar{y}_2$.

The unbiased estimate of the variance of the value y_i of the parameter in one unit is easy to obtain. So to estimate the variances of the estimates $\bar{y}$ in (1) and (2), we need to know the relations between:

- the variance of a mean of values (formula (1)) and the variance of an individual value;

- the variance of a weighted mean (formula (2)) from the variances of the various means.

More generally the definitive estimates of a mean of a parameter, from samples other than the unrestricted random ones, are functions of other partial estimates. The variances of these definitive estimates (and then of their sampling errors) can be estimated from the variances of the partial ones through the use of the following relationships.

322 Variances of some functions

322.1 Variance of a product of a random variate and a constant

We have $V(ky) = k^2V(y)$ where y is the random variate and k is the constant.

For instance, if $\bar{y}$ is an estimate of the mean value of a parameter per unit in a simple random sample and N the total number of units of the population (which is supposed to be known exactly), the corresponding estimate of the total of the parameter over the whole population is:

$$\hat{Y} = N\bar{y}$$

and the variance of this total volume will be:

$$V(\hat{Y}) = N^2V(\bar{y})$$

322.2 Variance of a sum of independent random values

a) Independence of two random values

Two random values are independent if their covariance is zero (see paragraph 223 for the definition of covariance).

b) Examples of dependent random values

(i) Given a line (population) of 1,000 trees (units) along a roadside we want to have an estimate of the mean reference diameter (DBH) per tree by means of a systematic sample of 50 trees, one tree every 20 trees. The rank number of the first sample tree will be selected at random among the numbers from 1 to 20, for instance 13, and the following sample trees will be the 33rd, the 53rd ... until the 993rd. The estimate of the mean DBH will be equal to:

$$(\overline{DBH}) = \frac{(DBH)_{13} + (DBH)_{33} + \dots + (DBH)_{993}}{50}$$

More generally, if $k = \frac{N}{n}$ (N being the total number of units of the population and n the number of units of the sample), the estimate of the mean of a parameter y from a systematic sampling can be expected to be as follows:

$$\bar{y} = \frac{y_i + y_{i+k} + \dots + y_{i+(n-1)k}}{n} \quad \text{with} \quad 0 < i \leq k$$

There are k pairs of values (y_i, y_{i+k}), from i = 1 to i = k. The values y_i and y_{i+k} will not be statistically independent if their covariance is not zero, that is to say if:

$$\text{cov}\,(y_i, y_{i+k}) = \frac{\sum_{i=1}^{k} (y_i - \bar{y}_1)\,(y_{i+k} - \bar{y}_2)}{k} \neq 0$$

where

$$\bar{y}_1 = \frac{\sum_{i=1}^{k} y_i}{k}$$

and

$$\bar{y}_2 = \frac{\sum_{i=1}^{k} y_{i+k}}{k}$$

Likewise the values y_i and y_{i+2k} may also not be statistically independent if $\text{cov}\,(y_i, y_{i+2k}) \neq 0$, which means that even the double interval (2k) between the trees is not enough. More generally, the same reasoning can be applied to any pair of the random values y of the numerator of $\bar{y}$.

In the example of the roadside trees, this independence may not be fulfilled if, for example, the distance between two consecutive sample trees is too small (possible interaction between trees), or if this interval is more or less the same as the "waveleng of certain soil characteristics.

c) Estimates from samples are not independent if the samples themselves are depend

Let us again consider the two stands from the example given in paragraph 321, and let us suppose that sampling is not independent in these two strata: this means that the number and/or the composition of all the contemplated samples in the second stratum is dependent on the selected sample in the first stratum (or vice versa).(1) It is eas

(1) This could be the case if, in order to avoid too expensive a forest inventory, it were decided for the second stratum to select only from those with a small proportion of sample plots with difficult access when the sample from the first stratum already has a relatively large number of such plots. It is obvious in this case that the number and the composition of all possible samples in the second stratum will depend on the sample selected in the first stratum.

to demonstrate that in this case $\bar{y}_1$ and $\bar{y}_2$ (estimates of the mean of a parameter y respectively in the first and second strata) are statistically dependent estimates, which means that their covariance is not zero:

$$\text{cov}\ (y_1, y_2) = \frac{\sum_{j,k} (\bar{y}_{1j} - \bar{Y}_1)\ (\bar{y}_{2k} - \bar{Y}_2)}{M_1 \times M_2} \neq 0$$

where $\bar{Y}_1$ and $\bar{Y}_2$ are the true values of the means per unit in respectively the first and second strata, $\bar{y}_{1j}$ and $\bar{y}_{2k}$ are respectively the estimates of $\bar{Y}_1$ from the sample j in the first stratum and of $\bar{Y}_2$ from the sample k in the second stratum.

M_1 and M_2 are the numbers of possible samples of the given types in the strata 1 and 2, the sum $\sum_{j,k}$ being extended to all the $M_1 \times M_2$ cross products $(\bar{y}_{1j} - \bar{Y}_1)\ (\bar{y}_{2k} - \bar{Y}_2)$.

d) It can be demonstrated that the variance of the sum of independent random values is the sum of the variances of these values.

If $y = \sum_i y_i$, the y_i being independent,

$$V(y) = \sum_i V(y_i)$$

322.3 Variance of the estimate of a mean from a simple random sample for an infinite population

We have $\bar{y} = \dfrac{y_1 + y_2 + \ldots + y_n}{n}$ and the y_i are independent

By application of the two former theorems we will have:

$$V\ (\bar{y}) = \frac{1}{n^2} \left[V\ (y_1) + V\ (y_2) + \ldots + V\ (y_n) \right]$$

All the n variances between brackets are equal to the variance $\sigma^2(y)$ of the values of the parameter over the whole population and we will have the very important result:

$$\boxed{\sigma^2(\bar{y}) = V(\bar{y}) = \frac{\sigma^2(y)}{n}}$$

The variance of the estimate of the mean in simple random sampling is equal to the variance of the value of the parameter over the whole population divided by the number of sampling units in the sample.

Consequently the sampling error on the estimate of the mean (which is proportional to the square root of the variance when n/N is small), will be inversely proportional to the square root of the number of the sampling units.

Case of finite populations

The former results are valid for infinite populations or for finite populations when the sampling fraction (or sampling intensity) $f = \frac{n}{N}$ is relatively small (say 5%).

In the case of finite populations, the sampling theory shows that in fact we have:

$$\sigma^2(\bar{y}) = \frac{\sigma^2(y)}{n}\left(1-\frac{n}{N}\right) = \frac{\sigma^2(y)}{n}(1-f)$$

and
$$\sigma(y) = \frac{\sigma(y)}{\sqrt{n}}\sqrt{1-f}$$

The terms $1-f$ and $\sqrt{1-f}$ are called the "finite population corrections" and may be neglected if f is small.

The introduction of these terms can be justified a posteriori: if the sampling becomes a complete census, standard error (or sampling error) must be equal to 0. This result can be obtained from the above formula as, in this case, $f = 1$.

322.4 Variance of a weighted linear expression of random values

If we have: $y = a_1y_1 + a_2y_2 + \dots + a_py_p = \sum_{i=1}^{p} a_iy_i$

(a_1, a_2 ... a_p being positive or negative constants)

the application of theorems from 322.1 and 322.2 gives:

$$V(y) = a_1^{\ 2}\,V(y_1) + a_2^{\ 2}\,V(y_2) + \dots + a_p^{\ 2}\,V(y_p) = \sum_{i=1}^{p} a_i^{\ 2}\,V(y_i)$$

In the case of the second example of paragraph 321 we will have:

$$V(\bar{y}) = \frac{S_1^{\ 2}}{S^2}V(\bar{y}_1) + \frac{S_2^{\ 2}}{S^2}V(\bar{y}_2)$$

This theorem is sometimes called "theorem of propagation of errors" and is used for stratified random sampling.

322.5 Variance of products and ratios of two independent random values

Let x and y be two independent random values, the variances of which are small in comparison with the squares of their respective values. We will have the approximate formulae:

$$V(xy) = y^2\,V(x) + x^2\,V(y)$$

$$V\left(\frac{y}{x}\right) = \left(\frac{y}{x}\right)^2\left[\frac{V(x)}{x^2} + \frac{V(y)}{y^2}\right]$$

322.6 Variance of functions of dependent random values

If $y_1, y_2, \ldots y_p$ are dependent random values and $a_1, a_2 \ldots a_p$ positive or negative constants, the variance of y:

$$y = a_1 y_1 + a_2 y_2 + \ldots + a_p y_p = \sum_{i=1}^{p} a_i y_i$$

will be:
$$V(y) = \sum_{i=1}^{p} a_i^2 V(y_i) + 2 \sum_{i \neq j} a_i a_j V(y_i, y_j)$$

where the sum $\sum_{i \neq j}$ is extended to all the different possible combinations of i and j, j being different from i, and $V(y_i, y_j)$ is the covariance between y_i and y_j.

If $a_1 = a_2 = \ldots = a_p = \frac{1}{p}$ and the y_i are the values of the same parameter in the p consecutive equal size sampling units of a systematic sample, y is, in this case, the estimate of the mean per unit from this sample and can be written $\bar{y}$. Its variance

$$V(\bar{y}) \neq \frac{V(y)}{p} = \sum_{i=1}^{p} a_i^2 V(y_i),$$ for the covariances $V(y_i, y_j)$

which make up the additional term will, in most cases, not be equal to 0.

More generally, it can be said that the application of the formula of random sampling for the estimate of the variance of the estimated mean is not valid in many systematic sampling designs for many parameters. In a systematic forest inventory, the equidistance between neighbouring sampling units will have to be sufficiently long in order to avoid any positive (or negative) covariance (or "correlation") between the respective values of a given parameter, if one wants to apply the relation $V(\bar{y}) = \frac{V(y)}{p}$

Product and ratio of two dependent random values

In this case, provided that the variances are small in comparison with the squares of the respective random values, the formulae of paragraph 322.5 become:

$$V(xy) = y^2 V(x) + x^2 V(y) + 2xy\, V(x, y)$$

$$V\left(\frac{y}{x}\right) = \left(\frac{y}{x}\right)^2 \left[\frac{V(x)}{x^2} + \frac{V(y)}{y^2} - 2\frac{V(x, y)}{xy}\right]$$

V (x, y) being the covariance between x and y.

33 Ratio estimates

The precision of the estimate of the mean of a parameter y is increased if we can relate it to another parameter x, which is known exactly for the population, or is known more precisely from a large sample. On the other hand, one may be interested in knowing not the single parameter y but rather a combination of it with one or more other parameters. In forest inventory if we have sampling units of different size, we will

have to know two random values in each sampling unit:

- the value y_i found in the unit for the parameter y itself;
- the area x_i of this unit.

The requested estimate will be essentially an estimate of the mean value of the parameter y per area unit (not per sampling unit), which in fact corresponds to the ratio $\frac{y}{x}$ of the two parameters.

Because in many forest inventories, sampling units will not have the same size, the use of an auxiliary variate x related in general to the size of the sampling unit appears to be necessary in many cases. The model of the relationship between y and x used is, essentially, a linear one:

$$y = a + bx \quad \text{("linear regression estimates")}$$

$$\text{and often } y = bx \quad \text{("ratio estimates")}$$

The first model is acceptable if the relationship between the two parameters is strong and may be satisfactorily represented by a straight line. It is equivalent to say that the correlation coefficient must be as close to 1 as possible. For efficient use of the second model it is necessary, in addition, for the line to go through the origin; in other words when x and y tend to 0 together. This is particularly the case of the variates "area of a sampling unit" and "any usual forest parameter": when the area tends to be 0, the forest parameters tend also to be 0.

That is why ratio estimates are used in forest sampling.

Two types of ratio estimates are commonly used in simple random sampling and they are:

$$\hat{R} = \frac{\bar{y}}{\bar{x}} = \frac{\sum_{i=1}^{n} y_i}{\sum_{i=1}^{n} x_i} \qquad \text{"ratio of the means"}$$

and

$$\hat{r} = \frac{1}{n} \sum_{i=1}^{n} \frac{y_i}{x_i} \qquad \text{"mean of the ratios"}$$

Paragraph 322.6 indicates how to obtain an acceptable estimate of the variance of $\hat{R}$, provided that the variances are small in comparison with the squares of the respective estimates $\bar{x}$ and $\bar{y}$.

34 Optimization(1) in design

341 Optimisation of a sampling design. The most efficient sampling design is the one that for a specific cost gives the smallest error for the parameter to be estimated or for an accepted error is the least expensive.

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(1) Optimization is used in the sense of setting out and selection of the most efficient or optimum design.

341.1 Problems related to optimization.

Definition of efficiency is easy, however to find the most efficient design is much more complicated because of a number of problems, some of which are:

a) For practical reasons all the possible sampling designs are not considered when selecting the design to be used. Some characteristics of the contemplated design are taken for granted. In the case of field sampling the area of the units at each stage, the number of stages and the stratification are fixed prior to optimization. This is usually based on previous experience. It must be emphasized that this leads to partial rather than absolute optimization. There is such an "optimum" design for each set of predetermined characteristics. In many textbooks and manuals the calculation of optimization is restricted to the estimation of the optimum number of sampling units at each stage based on a simple cost formulation.

b) A complete estimation of the error should take into consideration not only the sampling error but also biases and measurement errors (see paragraph 24). These latter are generally difficult if not impossible to determine. In most cases efficiency studies deal only with sampling errors and they are valid insofar as the measurement errors are reduced to a minimum. Elimination or reduction of measurement errors is often more important than the exact optimization of the sampling design.

c) A third problem occurring in the determination of the optimal sampling design is related to parameters. A sampling design is optimal for the estimation of a given parameter (say, gross volume over 60 cm diameter of a commercial species) but not for any other one (say, gross volume over 60 cm diameter of a group of commercial species). When designing the inventory it is therefore essential to select the most important parameter and to look for the most efficient design for the estimation of this parameter. Very often it is difficult to single out the most important parameter from those it is necessary to estimate. Even when one species only is very important, as in the case of Okoumé in Gabon or Pine in tropical pine forests, there may be various other useful parameters. In addition to the volume of the exploitable trees of the particular species, it is important to know precisely, for management purposes, the number of stems in the lower diameter classes. In any case the inventory officer must avoid a sampling design based on irrelevant parameters. One such case is where the selection of "the gross volume of all species over 10 cm diameter" has been used as a basic parameter for designing an inventory in a tropical forest where few species are utilized. This is generally not valid but it has been done frequently.

d) In a sampling design, the sampling error on a given parameter depends on, among other things, the variability of this parameter in the units of the sampled population. For optimizing the design, one must have a prior estimate of this variability. This knowledge can be obtained from former inventories, however in many cases there is no possible source of information and a small preliminary sampling is needed to have an estimate of the variances and coefficients of variation which are included in the sampling error formula. This small pilot inventory is also necessary for estimating cost figures which will be used for the optimization of the sampling design.

341.2 Mathematical formulation of an optimization

Let us express the precision of a given sampling by the standard error of the estimate, SE, of the parameter which has been selected as the most important, and the cost of it by C. SE and C are functions of various characteristics of the design, such as the size of a sampling unit and the number of sampling units or the sampling intensity in the case of a simple random sampling. Let us call these characteristics $x_1, x_2 \dots x_p$.

We have:

$$SE = SE\ (x_1, x_2, \dots x_p)$$

$$C = C\ (x_1, x_2, \dots x_p)$$

a) Let us suppose that the total cost of the inventory is already fixed and equal to Co. We will have in this case to minimize the standard error SE. So we must have:

$$SE\ (x_1, x_2, \dots x_p) = \text{minimum}$$

with $$C\ (x_1, x_2, \dots x_p) = C_o$$

It is demonstrated that the suitable values $(x_1)_0, (x_2)_0 \dots (x_p)_o$ of the characteristics $x_1, x_2, \dots x_p$ will be determined by resolving the following system of $p + 1$ equations with the $p + 1$ unknowns $x_1, x_2, \dots x_p, \lambda$:

$$\begin{cases} \dfrac{\partial SE}{\partial x_1} + \lambda \dfrac{\partial C}{\partial x_1} = 0 \\[2ex] \dfrac{\partial SE}{\partial x_2} + \lambda \dfrac{\partial C}{\partial x_2} = 0 \\ - - - - - - - - - - - - - - - \\ \dfrac{\partial SE}{\partial x_p} + \lambda \dfrac{\partial C}{\partial x_p} = 0 \\[2ex] C(x_1, x_2, \dots x_p) - C_o = 0 \end{cases}$$

$\dfrac{\partial SE}{\partial x_i}$ and $\dfrac{\partial C}{\partial x_i}$ standing for the partial derivatives of SE and C with respect to the characteristic x_i.

b) Let us suppose that a given precision of the estimate of the parameter at a given probability level is wanted. In this case the standard error will be fixed and equal to a given value $(SE)_o$. In this case we have to minimize the cost C and this is expressed by:

$$C\ (x_1, x_2, \dots x_p) = \text{minimum}$$

$$\text{with}\quad SE\ (x_1, x_2, \dots x_p) = (SE)_o \qquad (1)$$

The suitable values $(x'_1)_0\ (x'_2)_0 \dots (x'_p)_0$ will be determined by resolving the same system of equations, the last equation of the system being replaced by the equation (1). It can be noted that the first p equations are the same and that the solutions $(x_1)_0, (x_2)_0 \dots (x_p)_o$ are linked by the same (p-1) equations.

c) Numerical application.

Let us consider all the possible simple random field sampling designs (using area elements as sampling units) for the estimation of a given parameter over a forested area to be inventoried. Let us assume that we have found <u>empirically</u> from a pilot inventory and/or former inventories that the standard error SE of the estimate of this parameter can be expressed approximately by the following relation:

$$SE = \frac{a \log s + b}{\sqrt{ns}}$$

s being the area of the sampling unit of a sample

$\log s$ being the naperian logarithm of s

n being the number of the sampling units of the sample

a and b being coefficients

Let us assume that the total cost C of this sampling is satisfactorily expressed by the following formula:

$$C = \alpha + \beta n + \gamma ns$$

α being the fixed cost independent of the size of the sampling

β being the cost of access to one sampling unit

γ being the cost of enumeration per area unit

If the total cost of the inventory is known and equal to C_o, the optimal area of a sampling unit s_o and the optimal number of sampling units n_o will be the solution of the following system of equations:

$$\begin{cases} \dfrac{\partial SE}{\partial s} + \lambda \dfrac{\partial C}{\partial s} = o \\[2ex] \dfrac{\partial SE}{\partial n} + \lambda \dfrac{\partial C}{\partial n} = o \\[2ex] \alpha + \beta n + \gamma ns = Co \end{cases}$$

Eliminating from the two first equations we have

$$\frac{\partial SE}{\partial s} \cdot \frac{\partial C}{\partial n} - \frac{\partial SE}{\partial n} \cdot \frac{\partial C}{\partial s} = o \qquad (2)$$

If we replace these derivations by their right expressions in formula (2) and simplify, we find out that the solution s_o (optimal value of the size of the sampling unit) is such that it fills the following equation:

$$\log \quad - \left(2 \frac{\gamma}{\beta} s_o + 2 - \frac{b}{a}\right) =$$

s_o can be determined by a graphical way: it is the s-ordinate of the point where the respresentative curve of the function $y = \log s$ crosses the straight line representative of the function $y = 2 \frac{\gamma}{\beta} s + 2 - \frac{b}{a}$

The corresponding optimal value of n, n_o, is easily calculated from the relation

$$\alpha + \beta \qquad \gamma n_o s_o = C_o \qquad \text{or} \qquad n_o \quad \frac{C_o - \alpha}{\beta + \gamma s_o}$$

342 Optimization of an inventory design. The definition of the optimum inventory design is identical to that of a sampling design given in paragraph 341. The problems of optimization of an inventory design are similar to those quoted for a sampling design but are more difficult to solve because an inventory design often consists of a series of several sampling designs, e.g. one for the estimation of the areas, another for the field estimation of the mean number of stems per diameter class and a third for the assessment of the volumes of trees through volume tables. The most efficient inventory design might not be a combination of various optimal sampling designs. It can be imagined that it might be better to calculate the appropriate volumes from measurements taken on standing trees within the sampling units rather than build up volume tables from a selection of sample trees. This would eliminate the need for the third sampling design. In the same example it might be more efficient to estimate areas from the field sample rather than estimate them through the interpretation of aerial photographs. In most cases it is too difficult to make an exhaustive efficiency study prior to selecting an outline for the inventory design. This is often done on the basis of a rough estimation of the general cost and precision involved but also considering such factors as documentation available - aerial photographs, maps, volume tables, etc.- the skill of the workers, the transportation facilities and others. Once the general structure of the inventory design has been decided, efficiency studies are made for each of the sampling designs. Though this method is not theoretically the best, it cannot be avoided in most cases.

4 Classical sampling designs

41 Classification of sampling designs

411 Characteristics of sampling designs. A sampling design is defined by a combination of characteristics which correspond to the following items:

411.1 Nature of the units of the population

The same forested area can be considered as a population of either trees, plots (of the same or different areas), points or lines. It is very important to specify from the beginning what is to be considered as a unit of the population, since the ultimate sampling units are selected from these units. In particular, if the forested area is cons dered as a population of units of equal size, the unit area is to be specified. When one wants to characterize the variability of a given parameter, one should always give the coefficient of variation (see paragraph 223 of this chapter) with the mention of the area of the unit to which this coefficient refers. The variability of two parameters cannot be compared if their coefficients of variation refer to two different areas of the units.

411.2 Use of an auxiliary parameter

Under certain circumstances, as in the case of units of different size, and to improve the precision of the estimates, the parameters are combined with another one, called auxiliary variate. The estimation of this auxiliary variate may not be an objective of the inventory but its use as an intermediate parameter is necessary and

generally advantageous. Two main cases can be considered:

- an additional sampling is performed in order to obtain an estimate of the auxiliary variate: this is the case of the sampling design called double sampling (or two-phase sampling);

- there is no special (or additional) sampling: in the framework of the normal sampling design the auxiliary variate is recorded together with the parameters to be estimated. This is the case of sampling designs for ratio (or regression) estimates, the total of the auxiliary parameter over the whole parameter being known.

411.3 Number of stages

If the sampling is done directly among the units of the population, the sampling is called a one-stage sampling.

It may happen that for the sake of convenience, the population is considered at the first stage as a population of groups of units; a sampling is then done among these groups (called primary units). At the second stage, a sampling of units (secondary units) is done within each group selected during the first stage. The whole sampling operation is called a two-stage sampling. This design must not be confused with cluster sampling (see paragraph 412).

Other intermediate stages may be included, and more generally these samplings are called multi-stage sampling designs. The size of an intermediate unit will be defined by the number of units of the next stage it contains.

In forestry, there are many examples of two-stage sampling designs, some of three-stage and probably very few with a larger number of stages.

411.4 Other characteristics

The following characteristics are relative to any stage of a sampling design.

- Stratification

In order to reduce the variability of a parameter within the whole population and consequently the sampling error of the estimate, it is generally most appropriate to divide the population into more homogeneous (with respect to this parameter) sub-populations or strata and to make a separate sampling within each stratum. In this case the corresponding stage of the design is said to be stratified. Stratification is sometimes effected by taking into consideration an existing and useful sub-division of the population: this is the case when the population is a forested area already subdivided in geographical natural units (catchment areas, basins).

The stratification may be done prior to selection of the sample (this is the true stratification or "stratification a priori") or after selection of the sample (in this case it is called "stratification a posteriori").

In a two-stage sampling, stratification may occur in the first stage, where groups of units called "primary units" are distributed among different strata, or in the second stage, or in both stages.

- Random or systematic selection

Sampling theory is applicable in principle, only when sampling is made at random by using one of the numerous possible devices. For instance, in a plantation with a constant spacing of trees, a simple random sampling design may be obtained through the selection of

numbers from a table of random numbers after having numbered all the trees of the plantation.(1)

Sometimes, for practical reasons or for reasons directly related to the estimation of the parameters (for the mapping of forest types in the case of some forest inventories) it is more convenient to use systematic sampling at one or all the stages of the sampling design. If we have to inventory a line of trees (units), a systematic sampling will consist of the selection of one tree every p trees (the sampling intensity being $f = {}^1/_p$); if we have to inventory a forested area we may distribute the sample according to a grid laid on the map, each point of the grid being the centre of a sampling unit.

Although sampling theory does not provide users with a completely satisfactory estimate of the sampling error in systematic sampling designs, it is possible to get acceptable ones by using certain devices, some of which are listed in paragraph 423 of this chapter.

- Selection with or without replacement

As already said in paragraph 233, most of the sampling designs are considered "with replacement" although they are in fact "without replacement" as the same unit is not considered twice as a sampling unit (or in other words, as the sampling units in a given sample are all different units). All sampling designs listed in paragraph 42 are considered as if they were with replacement. This approximation is more acceptable as the sampling fraction (number of sampling units with respect to total number of units) gets smaller.

- Selection with equal or unequal probabilities

At a given stage of a sampling design, units may be selected with equal or unequal probabilities (see paragraph 233). In some sampling designs units are selected with probabilities proportional to their size (PPS). This sometimes proves to be very efficient. This is the case of two-stage forest sampling designs in which the units at the first stage ("primary units") are selected with probabilities proportional to their area of forest.(2)

- Equal or unequal size of the units

Let us assume that a rectangular forested area to be inventoried is divided arbitrarily in equal square blocks of, say, 1 km^2. Let us consider that the population is the whole area, including the non-forested parts. In this case the units can be the entire blocks and will be of equal size. However, if we consider that the population is restricted to the forested parts of the area, the units will be the forested part of each block and will not be the same size

In both cases these blocks can be selected with either equal or unequal probabilities (for instance in the case of unequal sized blocks probabilities might be proportional to the sizes). Blocks may be the ultimate units (in which case the sampling design will be

(1) If there are less than 1,000 rows and 1,000 columns in the whole population, each tree might be numbered by a 6-digit number, 3 digits for the number of its row and 3 digits for the number of its line.

(2) The use of the expression "PPS sampling" for "point sampling" in which trees are selected at each point by the prism or the Bitterlich Relaskop (i.e. proportionally to their basal area) is not correct as the sampling units are the points themselves (or eventually clusters of points) and not the trees.

a one-stage sampling design) or they may be the primary units of a two-stage sampling design with secondary units being for example plots of equal area.

- Equal or unequal number of sampling units per unit of the prior stage (multi-stage sampling designs)

There may be a different number of secondary units selected per primary unit in a two-stage sampling design. When the primary units are of equal size, the sampling intensity in the second stage (i.e. the ratio of the number of secondary units selected in a primary unit to the total number of secondary units per primary unit) may vary from unit to unit. When the primary units are of unequal size, the number of secondary units selected may be proportional to the size of the primary units (and in this case the sampling intensity at the second stage remains constant).

412 Clusters and record units. Generally the term cluster is used to define a sampling unit which is in fact a group of smaller units. The cluster is the statistical unit whereas the smaller ones are only record units. Information is collected separately in each record unit and is then merged with information from the other record units to constitute the information related to the sampling unit (cluster). The record units are not the statistical units. In no case should cluster sampling be understood as being synonymous with two-stage sampling. More generally stages of a sampling design and clustering are two different concepts which can co-exist as it is easy to build up a multi-stage sampling design wherein the sampling units at different stages are clusters.

42 Classical sampling designs used in forestry

421 Introduction. Below are listed some classical sampling designs used in forestry. They are not inventory designs. These will be dealt with in Chapter 7. As we have already seen, a forest inventory design is generally a combination of sampling designs.

All the sampling designs listed below, like any sampling design, may or may not use cluster sampling. As we have seen in the last paragraph, clustering is a sub-division of the sampling unit into smaller units. It can be applied at any stage of the sampling and it does not influence the respective formulas.

For each sampling design, two formulae will be given:

- the expression of the best estimate of the mean value of a parameter over the whole population per sampling unit of the last stage ("ultimate sampling unit") in case of equal size of these units or per size unit in case of unequal size;

- the expression of the best estimate of the variance of this estimate of the mean: as we have seen in paragraph 312 the corresponding sampling error at a given probability level is proportional to the square root of the variance provided that the assumption of normal distribution is acceptable.

Estimation of a proportion: The proportion of units of a population having a given characteristic (for instance proportion of units of a forested area belonging to a given forest type) can be considered as the mean value per unit of a particular parameter, the only values of which are 1 if the unit has the characteristic and 0 if it has not. The general formulae apply for this parameter but can be expressed more simply. The corresponding simplified formulas will be given for the most usual designs. For the other designs they will be easily established by keeping in mind that the corresponding parameter can have only the two values 0 or 1.

422 Random sampling designs (not systematic). The following table includes the random sampling designs considered in this paragraph. The figures refer to the relevant sub-paragraphs.

<table>
<tr><th>Type of sampling</th><th>Number of stages</th><th>Size of the units at the first stage</th><th>Size of the units at the second stage</th><th>Stratification of the units of the first stage</th><th>Stratification of the units at the second stage</th></tr>
<tr><td rowspan="13">area elements or trees (or points or lines for estimation of proportions)
422.1</td><td rowspan="6">one stage
.11</td><td rowspan="3">equal size (equal probabilities)
.111</td><td rowspan="6">n/a</td><td>unstratified
.111.1</td><td rowspan="6">n/a</td></tr>
<tr><td>stratified prior to sampling
.111.21</td></tr>
<tr><td>stratified after sampling
.111.22</td></tr>
<tr><td rowspan="3">unequal size (equal probabilities
.112</td><td>unstratified
.112.1</td></tr>
<tr><td>stratified prior to sampling
.112.21</td></tr>
<tr><td>stratified after sampling
.112.22</td></tr>
<tr><td rowspan="7">two stages (with same number of secondary units per primary unit)
.12</td><td rowspan="5">equal size (equal probabilities)
.121</td><td rowspan="4">equal size
.121.1</td><td rowspan="2">unstratified
.121.11</td><td>unstratified
.121.111</td></tr>
<tr><td>stratified
.121.112</td></tr>
<tr><td rowspan="2">stratified
.121.12</td><td>unstratified
.121.121</td></tr>
<tr><td>stratified
.121.122</td></tr>
<tr><td>unequal size</td><td>unstratified
.121.2</td><td>unstratified</td></tr>
<tr><td>unequal size (probability proportional to size)</td><td>equal size</td><td>unstratified</td><td>unstratified</td></tr>
<tr><td colspan="4">.122</td></tr>
<tr><td>point or line sampling
.2</td><td colspan="5">(no special design studied; only indication of some important characteristics of this type of sampling)</td></tr>
</table>

422.1 Units = area elements or trees (or points or lines for estimation of proportions)

Sampling using angle gauges, wedge prisms or Spiegel Relaskops is excluded from this class of design (for these designs see paragraph 423.2 "Point or line sampling designs").

422.11 One stage sampling designs

We will consider only the designs in which units are selected with equal probability. The symbols used are listed below:

f sampling intensity (or sampling fraction): $(f = \frac{n}{N})$

f_h sampling intensity (or sampling fraction) in the stratum h $(f_h = \frac{n_h}{N_h})$

h index of a stratum

i index of a unit

$(hi$ index of a unit (i) in a stratum (h))

L total number of strata (h = 1 to L)

n number of units in the sample

n_h number of units in the sample of stratum h

N total number of units in the population

N_h total number of units in the stratum h

p estimate of a proportion P from the sample

$\hat{R}_1$ estimate of the mean value per size unit of the parameter y ("ratio of the means" estimate) with a measure of size x as an auxiliary parameter.

s_h^2 estimated variance of the parameter y in the stratum h

$$s_h^2 = \frac{\sum_{i=1}^{n_h}(y_{hi} - \bar{y}_h)^2}{n_h - 1}$$

V exact value of a variance of a given estimate

v estimated value from a sample of a variance of a given estimate

x auxiliary parameter (measure of size) in sampling with ratio estimate

x_i value of x in the i^{th} unit

x_{hi} value of x in the i^{th} unit of the stratum h

$\bar{x}$ estimate of the mean value per unit of x : $\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i$

$\bar{x}_h$ estimate of the mean value per unit of x in the stratum h: $\bar{x}_h = \frac{1}{n_h}\sum_{i=1}^{n_h} x_{hi}$

X total value of x over the whole population: $X = \sum_{i=1}^{N} x_i$

X_h total value of x over the whole stratum h: $X_h = \sum_{i=1}^{N_h} x_{hi}$

$\bar{X}$ exact mean per unit of x over the whole population: $\bar{X} = \frac{1}{N}\sum_{i=1}^{N} x_i = \frac{X}{N}$

y	parameter to be estimated
y_i	value of y in the i^{th} unit
y_{hi}	value of y in the i^{th} unit of the stratum h
$\bar{y}$	estimate of the mean value per unit of y in the population: $\bar{y} = \frac{1}{n}\sum_{i=1}^{n} y_i$
$\bar{y}_h$	estimate of the mean of y in the stratum h: $\bar{y}_h = \frac{1}{n_h}\sum_{i=1}^{n_h} y_{hi}$

422.111 Units of equal size

422.111.1 Unstratified random sampling (or "unrestricted random sampling" or "simple random sampling")

This sampling design has already been explained in paragraph 311. Let us recall the corresponding formulae:

estimate of the mean per unit:

$$\boxed{\bar{y} = \frac{\sum_{i=1}^{n} y_i}{n}} \tag{1}$$

estimate of the variance of $\bar{y}$:

$$\boxed{v(\bar{y}) = \frac{1-f}{n} \frac{\sum_{i=1}^{n}(y_i-\bar{y})^2}{n-1} = \left(\frac{1}{n} - \frac{1}{N}\right) \frac{\sum_{i=1}^{n}(y_i-\bar{y})^2}{n-1}} \tag{2}$$

Two remarks:

$$\sum_{i=1}^{n}(y_i-\bar{y})^2 = \sum_{i=1}^{n} y_i^2 - n\bar{y}^2 = \sum_{i=1}^{n} y_i^2 - \frac{\left(\sum_{i=1}^{n} y_i\right)^2}{n}$$

If f is small (for instance less than 0.01 = 1 percent) $1-f$ is approximately equal to 1 and we have:

$$\boxed{v(\bar{y}) = \frac{\sum_{i=1}^{n}(y_i-\bar{y})^2}{n(n-1)}} \tag{2'}$$

Estimation of a proportion P (of units having a given characteristic).

In this case we have $y_i = 1$ or 0 according to whether the unit i has the given characteristic or not.

Estimate of the proportion P:

$$\boxed{p = \frac{a}{n}} \tag{3}$$

where a is the number of units in the sample which have the given characteristic.

Estimate of the variance of p:

$$\boxed{v(p) = (1-f)\,\frac{p(1-p)}{n-1} = (1-\frac{n}{N})\,\frac{p(1-p)}{n-1}} \qquad (4)$$

If $1-\frac{n}{N}$ is small we get: $$\boxed{v(p) = \frac{p\,(1-p)}{n-1}} \qquad (4')$$

Remark: In the case of the estimation of a proportion related to a characteristic which can be attributed to a point itself (and not to a plot around the point) the units may be the points. This is the case where the estimation of the area of a given forest type is carried out on photographs or maps. In this case N is infinite and f is practically equal to zero and formula (4') is the right one.

422.111.2 Stratified random sampling

422.111.21 Stratification prior to sampling

The sizes N_h of the various strata are exactly known and the sampling is made independently in each stratum.

Estimate of the mean per unit $$\boxed{\bar{y}_{st} = \frac{\sum_{h=1}^{L} N_h \bar{y}_h}{N}} \qquad (5)$$

Estimate of the variance of $\bar{y}_{st}$ $$\boxed{v(\bar{y}_{st}) = \sum_{h=1}^{L} \frac{N_h^2}{N^2}\,\frac{1-f_h}{n_h}\,s_h^2} \qquad (6)$$

This formula can be written in different forms and may be simplified if the sampling fraction $f_h = \frac{n_h}{N_h}$ is constant whatever the stratum.

422.111.22 Stratification after sampling

The sizes N_h of the various strata can be determined exactly or fairly accurately, but there is only one sampling for the whole population (and not an independent sampling in each stratum) and the sampling units are classified into strata after they have been sampled. This is the case of a forest inventory in which:

stratum sizes are known by photointerpretation;

only one sampling is done for the whole area to be inventoried;

the fact that a unit belongs to a given stratum is not known or not investigated before data recording in the field.

Estimate of the <u>mean per unit</u>

$$\boxed{\bar{y}'_{st} = \frac{\sum_{h=1}^{L} N_h \bar{y}_h}{N}} \qquad (7)$$

<u>Estimate of the variance of $\bar{y}'_{st}$</u>

$$\boxed{v(\bar{y}'_{st}) = \frac{1-f}{n} \sum_{h=1}^{L} \frac{N_h}{N} s_h^2 + \frac{1}{n^2} \sum_{h=1}^{L} (1 - \frac{N_h}{N}) s_h^2} \qquad (8)$$

(where $n = \sum_{h=1}^{L} n_h$ is the total number of sampling units and $f = \frac{n}{N} = \frac{n_h}{N_h}$ whatever h is, as in this case there is only one sampling and thus only one sampling fraction).

If the estimated variances s_h^2 within the different strata are not too different and if the sample is large the second term of $V(\bar{y}'_{st})$ is small. This estimate is then not very different from the one for stratification prior to sampling given by formula (6).

Formula (8) assumes that there is no systematic error in the estimation of N_h.

422.112 <u>Units of unequal size</u> (ratio estimate)

If the statistical units of a forested area to be inventoried are strips or line plots, they will be in most cases of different size for one or several of the following reasons:

- irregular shape of the forested area;
- irregular contour of the different strata within the area;
- different sizes of the horizontal projections of the units (these projections being in fact the units) due to different terrain features from one unit to another.

In such cases a judicious approach is to consider <u>the size (area) of each unit as an auxiliary parameter</u> and to estimate the <u>mean value of the parameter per size unit as the ratio of the parameter itself over this auxiliary parameter</u> (see paragraphs 322.6 and 33).

422.112.1 **<u>Without stratification</u>**

Estimate of the mean value per size unit:
("ratio of the means")

$$\boxed{\hat{R}_1 = \frac{\sum_{i=1}^{n} y_i}{\sum_{i=1}^{n} x_i} = \frac{\bar{y}}{\bar{x}}} \qquad (9)$$

Estimate of the variance of $\hat{R}_1$:

$$\boxed{v(\hat{R}_1) = \frac{1}{\bar{X}^2} \frac{1-f}{n(n-1)} (\sum_{i=1}^{n} y_i^2 + \hat{R}_1^2 \sum_{i=1}^{n} x_i^2 - 2 \hat{R}_1 \sum_{i=1}^{n} x_i y_i)} \qquad (10)$$

If the sample estimate per sampling unit is $\bar{x} = \frac{\sum_{i=1}^{n} x_i}{n}$, then (10) may be written as follows:

$$\boxed{v(\hat{R}_1) = \hat{R}_1^2 \frac{1-f}{n(n-1)} \left(\frac{\sum_{i=1}^{n} y_i^2}{\bar{y}^2} + \frac{\sum_{i=1}^{n} x_i^2}{\bar{x}^2} - 2 \frac{\sum_{i=1}^{n} x_i y_i}{\bar{x} \cdot \bar{y}} \right)} \qquad (10')$$

Important remark: The ratio estimate $\hat{R}_1$ is a biased estimate but the bias will be the more negligible as:

- the number n of sampling units is larger;
- the regression between y and x is better represented by a straight line through the origin (this is generally well verified if y is a volume or number of stems and if x is the area of the unit).(1)

422.112.2 With stratification

422.112.21 Stratification prior to sampling

If the numbers n_h of sampling units in the strata are large enough and if the ratios $\hat{R}_h$ in the various strata are different enough, it is demonstrated that the best estimates of the ratio and of the variance of the estimate are the following:

Estimate of the mean per size unit ("separate ratio estimate"):

$$\boxed{\hat{R}_{1s} = \sum_{h=1}^{L} \frac{X_h}{X} \hat{R}_{1h} = \sum_{h=1}^{L} \frac{X_h}{X} \frac{\bar{y}_h}{\bar{x}_h}} \qquad (11)$$

Estimate of the variance of $\hat{R}_{1s}$:

$$\boxed{v(\hat{R}_{1s}) = \frac{1}{\bar{X}^2} \sum_{h=1}^{L} \frac{N_h^2}{N^2} \frac{1-f_h}{n_h(n_h-1)} \left(\sum_{i=1}^{n_h} y_{hi}^2 + \hat{R}_{1h}^2 \sum_{i=1}^{n_h} x_{hi}^2 - 2\hat{R}_{1h} \sum_{i=1}^{n_h} x_{hi} y_{hi} \right)} \qquad (12)$$

422.112.22 Stratification after sampling

If the variances of the $\hat{R}_{1h}$ are approximately the same in all strata, and if the sample is large enough, formula (12) may be applied; if not, formula (8) has to be adapted to the case of this ratio estimate.

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(1) In any case we have: $|\text{bias } \hat{R}_1| \leqslant \sqrt{V(\hat{R}_1)} \times \frac{\sqrt{V(\bar{x})}}{\bar{X}}$

where: $V(\hat{R}_1)$ is the exact variance of $\hat{R}_1$ (estimated by $v(\hat{R}_1)$)

$V(\bar{x}) = \frac{V(x)}{\sqrt{n}}$ is the exact standard error of $\bar{x}$ (standard deviation of x divided by $\sqrt{n}$).

422.12 Two-stage sampling designs

We will consider only the designs in which the same number of secondary units are selected per primary unit.

All the estimated means in the following formulae are means per secondary unit.

The symbols used are listed below:

f_1 sampling intensity at the first stage: $f_1 = \frac{n}{N}$ (equal primary units)

f_2 sampling intensity at the second stage: $f_2 = \frac{m}{M}$ (equal primary units and same sampling intensity at the second stage in all primary sampling units)

f_{2ki} sampling intensity at the second stage in the stratum ki of the primary unit i

h index of a stratum (stratification of primary units)

i index of a primary unit

j index of a secondary unit

(ij index of a secondary unit in a primary unit)

ki index of a stratum (stratification of secondary units) within the primary unit i

L total number of strata for primary units (h = 1 to L)

L_i' total number of strata for secondary units within the primary unit i (ki = 1 to L_i')

m number of secondary units in the sample of each primary unit

m_{ki} number of secondary units in the sample of stratum ki in the primary unit i

M total number of secondary units in one primary unit

M_{ki} total number of secondary units in stratum ki in the primary unit i

n number of primary units in the sample

n_h number of primary units in the sample of the stratum h

N total number of primary units in the population

N_h total number of primary units in the stratum h

p estimate of a proportion P from the whole sample

p_i estimate of a proportion P from the sample of primary unit i

s_{ki}^2 estimate of the variance of the parameter y in the stratum ki in the primary unit i

$$s_{ki}^2 = \frac{\sum_{j=1}^{m_{ki}} (y_{kij} - \bar{y}_{ki})^2}{m_{ki} - 1}$$

x auxiliary parameter (measure of size) in sampling with ratio estimation

x_{ij} value of x in the j^{th} secondary unit of the i^{th} primary unit

$\bar{x}_i$ estimate of the mean value per secondary unit of x in the primary unit i:

$$\bar{x}_i = \frac{1}{m} \sum_{j=1}^{m} x_{ij}$$

$\bar{\bar{X}}$ exact mean value per secondary unit of x over the whole population

y parameter to be estimated

y_{ij} value of y in the j^{th} secondary unit of the i^{th} primary unit

y_{hij} value of y in the j^{th} secondary unit of the i^{th} primary unit of the strrtum h

y_{kij} value of y in the j^{th} secondary unit of the stratum ki in the i^{th} primary unit

$\bar{y}_i$ estimate of the mean value per secondary unit of y in the primary unit i:

$$\bar{y}_i = \frac{1}{m} \sum_{j=1}^{m} y_{ij}$$

$\bar{y}_{ki}$ estimate of the mean value per secondary unit of y in stratum ki (primary unit i):

$$\bar{y}_{ki} = \frac{1}{m_{ki}} \sum_{j=1}^{m_{ki}} y_{kij}$$

$\bar{y}_{NSi}$ estimate of the mean value per secondary unit of y in primary unit i (with stratification within primary units):

$$\bar{y}_{NSi} = \sum_{ki=1}^{L_i'} \frac{Mki}{M} \bar{y}_{ki}$$

$\bar{\bar{y}}_h$ estimate of the mean value per secondary unit of y in stratum h:

$$\bar{\bar{y}}_h = \frac{1}{n_h m} \sum_{i=1}^{n_h} \sum_{j=1}^{m} y_{hij}$$

$\bar{\bar{y}}_{NSh}$ estimate of the mean value per secondary unit of y over the primary units of stratum h (with stratification within the primary units):

$$\bar{\bar{y}}_{NSh} = \frac{1}{n_h} \sum_{i=1}^{n_h} \bar{y}_{NSi}$$

422.121 Primary units of equal size

In the designs listed below, the primary units are selected with equal probabilities.

422.121.1 Secondary units of equal size

422.121.11 No stratification of primary units

422.121.111 No stratification of secondary units within primary units.

Estimate of the mean value per secondary unit:

$$\boxed{\bar{\bar{y}} = \frac{\sum_{i=1}^{n} \bar{y}_i}{n} = \frac{\sum_{i=1}^{n} \sum_{j=1}^{m} y_{ij}}{mn}} \qquad (13)$$

Estimate of the variance of $\bar{\bar{y}}$:

$$\boxed{v(\bar{\bar{y}}) = \frac{1-f_1}{n} \frac{\sum_{i=1}^{n} (\bar{y}_i - \bar{\bar{y}})^2}{n-1} + \frac{f_1(1-f_2)}{nm} \sum_{i=1}^{n} \sum_{j=1}^{m} \frac{(y_{ij} - \bar{y}_i)^2}{n(m-1)}} \qquad (14)$$

Estimation of a proportion

In this case the values of the parameter y in the secondary units are equal to 0 or 1 (y_{ij} = 1 or 0). The above formulae may be simplified.

Estimate of the proportion P (mean value of y per secondary unit):

$$\boxed{p = \frac{\sum_{i=1}^{n} p_i}{n}} \qquad (13')$$

(where p_i is the estimate of the proportion for the primary unit i: $p_i = \frac{a_i}{m}$, a_i being the number of units in the sample of the primary unit i for which $y_{ij} = 1$).

Estimate of the variance of p

$$\boxed{v(p) = \frac{1-f_1}{n} \frac{\sum_{i=1}^{n} (p_i - p)^2}{n-1} + \frac{f_1(1-f_2)}{nm} \sum_{i=1}^{n} \frac{p_i(1-p_i)}{n(m-1)}} \qquad (14')$$

If the secondary units are points, then the number M of secondary units per primary unit is infinite and $f_2 = 0$

422.121.112 Stratification of secondary units within primary units (prior to sampling)

Estimate of the mean value per secondary unit

$$\boxed{\bar{\bar{y}}_{NS} = \frac{1}{n} \sum_{i=1}^{n} \sum_{ki=1}^{L_i'} \frac{M_{ki}}{M} \bar{y}_{ki} = \frac{1}{n} \sum_{i=1}^{n} \bar{y}_{NSi}} \qquad (15)$$

Estimate of the variance of $\bar{\bar{y}}_{NS}$

$$v(\bar{\bar{y}}_{NS}) = \frac{1-f_1}{n} \frac{\sum_{i=1}^{n}(\bar{y}_{NSi} - \bar{\bar{y}}_{NS})^2}{n-1} + \frac{f_1}{n^2} \sum_{i=1}^{n} \sum_{ki=1}^{L_i'} \frac{M_{ki}^2}{M^2} \frac{1-f_{2ki}}{m_{ki}} s_{ki}^2 \qquad (16)$$

Formula (16) is similar to (14) and reduces to this latter when there is no stratification within the primary units. The nature and the number of the strata may not be the same in the various primary units.

422.121.12 Stratification of primary units (prior to sampling).

422.121.121 No stratification of secondary units within primary units.

Estimate of the mean value per secondary unit:

$$\bar{\bar{y}}_S = \sum_{h=1}^{L} \frac{N_h}{N} \cdot \frac{\sum_{i=1}^{n_h} \sum_{j=1}^{m} y_{hij}}{n_h \; m} = \sum_{h=1}^{L} \frac{N_h}{N} \cdot \bar{\bar{y}}_h \qquad (17)$$

Estimate of the variance of $\bar{\bar{y}}_S$

$$v(\bar{\bar{y}}_S) = \sum_{h=1}^{L} \left(\frac{N_h}{N}\right)^2 v(\bar{\bar{y}}_h) \qquad (18)$$

$v(\bar{\bar{y}}_h)$ being obtained by formula (14) wherein the primary units taken into consideration are those which belong to stratum h.

422.121.122 Stratification of secondary units within primary units (prior to sampling)

Let us refer the index h to the stratification of the primary units and the index k to the stratification of the secondary units within the primary units. These two stratifications must not overlap. In a forestry sampling design the stratification of primary units may be a geographical stratification (by catchment area) or a broad vegetation classification, while the stratification of the secondary units within each primary unit may be a stratification by density and height of the dominant trees ("condition classes").

Estimate of the mean value per secondary unit:

$$\bar{\bar{y}}_{SS} = \sum_{h=1}^{L} \frac{N_h}{N} \bar{\bar{y}}_{NS_h} \qquad (19)$$

$\bar{\bar{y}}_{NS_h}$ being calculated by formula (15) applied to the units of the stratum h.

Estimate of the variance of $\bar{\bar{y}}_S$

$$v(\bar{\bar{y}}_{SS}) = \sum_{h=1}^{L} \left(\frac{N_h}{N}\right)^2 v(\bar{\bar{y}}_{NS_h}) \tag{20}$$

$v(\bar{\bar{y}}_{NS_h})$ being calculated by formula (16) applied to the units of stratum h.

422.121. Secondary units of unequal size

In this case, ratio estimation is used as in one-stage sampling designs, the size of a secondary unit being the auxiliary parameter. We will consider only the case where there is no stratification either of primary units or of secondary units.

Estimate of the mean value per size unit
("ratio of the means")

$$\hat{R}_2 = \frac{\sum_{i=1}^{n} \bar{y}_i}{\sum_{i=1}^{n} \bar{x}_i} = \frac{\sum_{i=1}^{n} \sum_{j=1}^{m} y_{ij}}{\sum_{i=1}^{n} \sum_{j=1}^{m} x_{ij}} \tag{21}$$

Estimate of the variance of $\hat{R}_2$

$$v(\hat{R}_2) = \frac{1}{\bar{\bar{X}}^2} \frac{1-f_1}{n(n-1)} \left[\sum_{i=1}^{n} \bar{y}_i^{\,2} + \hat{R}_2^{\,2} \sum_{i=1}^{n} \bar{x}_i^{\,2} - 2\hat{R}_2 \sum_{i=1}^{n} \bar{x}_i \cdot \bar{y}_i \right] + \frac{1}{\bar{\bar{X}}^2} \frac{f_1(1-f_2)}{nm} \sum_{i=1}^{n} \sum_{j=1}^{m} \frac{\left[(y_{ij}-\bar{y}_i)^2 + \hat{R}_2^{\,2}(x_{ij}-\bar{x}_i)^2 - 2\hat{R}_2(y_{ij}-\bar{y}_i)(x_{ij}-\bar{x}_i)\right]}{n(m-1)} \tag{22}$$

422.122 Primary units of unequal size

We will consider only the case of the primary units being selected with a probability proportional to their sizes, without any prior stratification of the primary units or of the secondary units and with secondary units of equal size. Let us recall that we assume that there is the same number of secondary sampling units per primary unit.

Estimate of the mean value per secondary unit:

$$\bar{\bar{y}}_{PPS} = \frac{1}{n} \sum_{i=1}^{n} \bar{y}_i = \frac{1}{nm} \sum_{i=1}^{n} \sum_{j=1}^{m} y_{ij} \tag{23}$$

The formula is the same as (13) which gives the estimate $\bar{\bar{y}}$ for a two-stage sampling with equal primary units selected with equal probabilities (unweighted sample mean per secondary unit).

Estimate of the <u>variance of $\bar{\bar{y}}_{PPS}$</u>

$$v(\bar{\bar{y}}_{PPS}) = \sqrt{\frac{1}{n(n-1)} \sum_{i=1}^{n} (\bar{y}_i - \bar{\bar{y}}_{PPS})^2} \qquad (24)$$

The simplicity of formulae (23) and (24) and the usual efficiency of this design make it particularly interesting.

4??.? <u>Point (or line) sampling designs</u>

This type of sampling is used in the field work of a forest inventory. The ultimate units are points (or lines) and are not characterized by a given area or by a tree. At each point the trees (trees are <u>not</u> the sampling units) are selected with a probability proportional to one characteristic which is:

- its basal area in "horizontal point sampling"
- its diameter in "horizontal line sampling"
- the square of its height in "vertical point sampling"
- its height in "vertical line sampling".

In other words for each tree there is a corresponding area of plot proportional to this characteristic and the bigger this characteristic, the larger the plot. It is for this reason that this type of design is sometimes called "polyareal plot sampling".

These designs - in particular the "horizontal point sampling" - have developed very fast in the last twenty years in forestry, first in North America (using angle gauges or prisms), and then in other temperate zones (especially in Europe with the Spiegel Relaskop). Their use in tropical forests is hampered by limiting practical factors, such as the opacity of the undergrowth and the various heights of buttresses. In addition, these designs do not give directly a representative picture of the forest at each point because the trees are not selected with the same probability: this shortcoming is more serious in mixed tropical forests where it may be interesting to know the distribution of the species and diameter classes at each sampling location. However, it has been successfully used in some cases and may be recommended in the tropics in homogeneous stands (pine forests or plantations).

Except for this difference in the nature of the sampling units, all the designs described above are applicable. In particular, if the lines have different lengths, it is worthwhile using a ratio estimate with the length of the line as an auxiliary parameter. As in the case of area elements or trees, clustering may be used with any type of design.

Therefore it is not necessary to resume the designs listed above, and we will only mention what is to be changed in the formulae.

- <u>Value of the parameter in one point</u> (or in one line)

Let us take the case of a horizontal point sampling design. The point i being the ultimate sampling unit, the <u>value y_i of the parameter y per area unit in this unit</u> is equal to:

$$y_i = y_{i,1}\left(\frac{F}{BA_{i,1}}\right) + y_{i,2}\left(\frac{F}{BA_{i,2}}\right) + \dots + y_{i,k}\left(\frac{F}{BA_{i,k}}\right) + \dots + y_{i,pi}\left(\frac{F}{BA_{i,pi}}\right)$$

where: p_i is the total number of trees selected in point i

$y_{i,k}$ if the value of the parameter y for the k^{th} selected tree of the point i (if y is a number of stems, $y_{i,k}$ will be equal to 1 whatever k is).

$BA_{i,k}$ is the basal area of the k^{th} selected tree of the point i

F is the basal area factor (equal to $F = 10{,}000 \sin^2 \frac{\theta}{2}$, in square metres (basal area) per hectare, wherein θ is the gauge angle).

Similar formulae are applicable to the three other designs in which the basal areas of the trees are replaced by the relevant characteristics, diameter, square of height or height, and corresponding value of the factor F.

- Number of units - sampling intensities

Strictly speaking, as the population (and/or the strata, and/or the intermediate units) is a forested area, the sizes of the units are to be measured in areas. But as a unit has no defined area (there are as many areas as values of the characteristic) the total number of ultimate units in the population (or in any division of it) cannot be defined precisely. Provided that the total number of trees selected in all the units is relatively small compared to the total number of trees of the population (or of the related subdivision of it),

- the sampling intensity at the ultimate stage will be considered sufficiently low to be made equal to 0;
- the number of ultimate units at the last stage per intermediate unit of the former stage is so large that its inverse can be made equal to 0.

A very thorough analysis of the point and line sampling principles is given in "Forest Mensuration" by B. Husch, Ch. I. Miller and Th. W. Beers (page 254-291).

423 Systematic sampling designs

423.1 General considerations

By systematic sampling designs we mean all sampling designs at one, several or all stages at which a selection of sampling units is made according to a systematic pattern, i.e. by selecting only a first unit at random, the location of the other sampling units being automatically deduced from this first selection.

Any design which includes a systematic selection of the units is not strictly according to sampling theory for the following reasons:

- Only one unit is selected at random, the other units are not independently selected (in terms of statistics it is said that each one does not correspond to a "degree of freedom"); in this case the variance cannot be estimated. This can be understood also if we compare the whole systematic sample as a cluster. We have seen that the cluster can only be considered as a sampling unit (not the constitutive units) and no variance can be calculated from the value of the parameter in only one unit.

- Once the first unit is selected the other units, which do not belong to the future sample, have a zero-probability of being selected and the other units of the sample have a probability of being selected equal to 1. In other words most of the units of the population are definitely excluded from the selection because of the prearranged pattern of this systematic design. This is contrary to a basic principle of the sampling theory.

In addition to these considerations, it must be pointed out that any calculation of the variance of the mean is complicated by the fact that there may be dependence of the values of the parameter in couples of neighbouring units. In this case the estimate of the variance of the estimated mean is not simply related to the variance of the value of the parameter in one unit (see paragraph 322.3) and the calculation of an estimated variance of the mean becomes practically impossible.

All random designs listed in paragraph 422, with the exception of the two-stage sampling design with unequal probabilities, have one or more corresponding systematic ones: in particular, several possibilities of systematic designs exist, corresponding to each two-stage random design, whether the systematic selection is made at the first stage, at the second stage or at both stages.

423.2 Amendments to the formulae for random designs

423.21 Estimation of the means

The estimate of the mean value of a parameter per unit (or per size unit) in a systematic design is, in most cases, given by the same expression as for the corresponding random design. So the formulae given in paragraph 422 are generally applicable.

However, caution is necessary in the estimation of the mean value of some parameters. If there is a periodic trend in the values of a parameter and if the systematic design has the same "wavelength", the estimate of the mean might have a rather important bias. This may happen, for instance, if the topography is roughly a succession of parallel ridges and valleys and if the systematic layout of the sampling units is such that units appear mainly on the ridges (or in the valleys), the mean value of the parameter will be overestimated (or underestimated).

In order to avoid such troublesome coincidences, one would have to check very carefully that the distances between sampling units are not equal (or a multiple) of the "wavelength" of any periodic trend in the population.

423.22 Estimation of the variances of the estimated means

423.221 "Random parameters"

The distribution of the values of a given parameter in the units of a population may be "at random", which means that there is a very little or zero correlation between the values of a parameter in two different units whatever the distance between these two units (the corresponding covariances are equal to 0 - see paragraph 322.2). This is the case of some parameters related to species with a very little occurrence in some mixed tropical forests (the distribution of which is comparable to Poisson's distribution).

For such parameters the variances of the estimated means can be determined by the formula for the corresponding random design.

423.22 All other parameters

Many statisticians have studied the problem and, although there is no completely satisfactory estimation of the variances given by the sampling theory, some calculations give reasonably reliable estimates. We will give below some of the more usual ones. For the sake of simplicity we will limit ourselves to the one-stage simple systematic design. Extension of this case can be made easily for the stratified and/or two-stage systematic designs.

423.222.1 Units of equal size

First method: Stratification with overlapping strata with two sampling units

a) Let us suppose we have only one line of sampling units (plots or trees along a line) or that the sample consists of equal parallel and equidistant sampling units (strips or lines of plot-record units). An estimation of the variance is:

$$\boxed{v(\bar{y}) = \frac{1-f}{n} \; \frac{\sum_{i=1}^{n-1}(y_{i+1} - y_i)^2}{2(n-1)}} \qquad (24)$$

where $\bar{y}$ is the sample mean (estimate of the mean value per unit of the parameter

n is the number of sampling units

y_{i+1}, y_i are the values of the parameter respectively in the $(i+1)^{th}$ and i^{th} sampling units

$f = \frac{n}{N}$ is the sampling intensity (N total number of units in the population)

This formula is established by considering that the whole population is divided in (n-1) strata, each containing two neighbouring sampling units and each sampling unit belonging to two overlapping strata, with the exception of the first and last sampling units.

b) If we have several parallel and equidistant lines of sampling units it is worth considering another stratification of the lines: each line will belong to a strata the size of which is proportional to the number of sampling units along the line.

The formulae will be:

$$\boxed{\bar{y} = \sum_{h=1}^{m} \frac{N_h}{N} \bar{y}_h = \sum_{h=1}^{m} \frac{N_h}{N} \sum_{i=1}^{n_h} \frac{y_{ih}}{n_h} \simeq \frac{\sum_{h=1}^{m} \sum_{i=1}^{n_h} y_{ih}}{n}} \qquad (25)$$

where m is the number of lines

N_h is the total number of units in the stratum h (corresponding to line h)

N is the total number of units in the population (area inventoried)

$$N = \sum_{h=1}^{m} N_h$$

$\frac{N_h}{N}$ may be estimated by $\frac{n_h}{n}$ (where n_h and n are respectively the number of sampling units along the line h and the total number of sampling units: $n = \sum_{m=1}^{h} n_h$)

y_{ih} and $\bar{y}_h$ are respectively the value of y in the i^th sampling unit of line h and the estimated mean value of y per unit in line h:

$$\bar{y}_h = \frac{1}{n_h} \sum_{i=1}^{n_h} y_{ih}$$

In each stratum the variance $v(\bar{y}_h)$ can be estimated by the formula (24) where f, n and the differences $(y_i+1 - y_i)$ are restricted to the stratum and the estimated variance of $\bar{y}$ will be:

$$v(\bar{y}) = \sum_{h=1}^{m} \frac{N_h^2}{N^2} \; v(\bar{y}_h) \simeq \sum_{h=1}^{m} \frac{n_h^2}{n^2} v(\bar{y}_h) \qquad (26)$$

<u>Second method</u> - stratification with non-overlapping strata with 4 sampling units (for two-dimensional samples of areas only with a square or rectangular pattern).

Instead of considering strata containing two sampling units, we consider strata containing <u>four sampling units</u> (two units on a given line and the two corresponding ones on the next parallel line). If we take no overlapping strata we will have:

$$v(\bar{y}) = \frac{1-f}{n} \; \frac{1}{3n'} \; \left[\sum_{i=1}^{n} y_i^2 - 4 \sum_{j=1}^{n'} \bar{y}_j^2 \right] \qquad (27)$$

where $\bar{y}_j$ is the mean value of the parameter in the stratum j

n' is the number of strata: $n' \# \frac{n}{4}$

the other symbols having the same meaning as above.

423.222.2 <u>Units of unequal size</u>

We will limit ourselves to the case of <u>one line of unequal sampling units</u> or of <u>equidistant parallel sampling units of unequal size</u> (for instance strips of same width but of unequal length). <u>We will apply the first method of stratification with overlapping strata of two units</u>, and will consider the area x of a unit as the auxiliary parameter.

Estimate of the mean value of the parameter per size (area) unit:

$$\hat{R}_{1,sys} = \frac{\sum_{i=1}^{n} y_i}{\sum_{i=1}^{n} x_i} \qquad (28)$$

(same as (9))

Estimate of the variance of this estimate:

$$v(\hat{R}_{1,sys}) = \frac{1}{\bar{X}^2} \frac{1-f}{2n(n-1)} \left[\sum_{i=1}^{n-1} (y_{i+1} - y_i)^2 + \hat{R}^2_{1,sys} \sum_{i=1}^{n-1} (x_{i+1} - x_i)^2 - 2\hat{R}_{1,sys} \sum_{i=1}^{n-1} (x_{i+1} - x_i)(y_{i+1} - y_i) \right] \qquad (29)$$

(where the symbols are similar to the one used in paragraph 4 2.11).

CHAPTER IV

REMOTE SENSING AND MAPPING FOR AREA ESTIMATION IN FOREST INVENTORY

CHAPTER IV

REMOTE SENSING AND MAPPING FOR AREA ESTIMATION IN FOREST INVENTORY

1 Introduction

Most forest inventories aim at providing satisfactory estimates of total values of parameters of the forests (mainly volumes of wood) over the whole inventoried area and/or over parts of it. These total values are obtained through estimation of the corresponding area and estimation of the mean values per area unit of these parameters.

Both areas and mean values of the parameters per area unit may be estimated through use of aerial photographs (and maps) and/or field measurements and observations, these estimations being made by complete census or by sampling.

We will not consider in this edition the case of the estimation of the mean values per area unit of the parameters made completely or partially through use of aerial photographs (or any other remote sensing data), since such techniques are mostly restricted to some fairly uniform temperate forests and plantations and are for the time being of little relevance for tropical countries. Difficulty of species identification from aerial photographs in the tropics, loose correlation between crown characteristics and bole dimensions, and the impossibility of defect assessment from aerial photographs severely limits the applicability of photogrammetric measurements in surveys of tropical forests. However, some literature is quoted in Appendix II which should be consulted in case such methods appear feasible in the tropics (for instance in plantations).

As indicated by the title, this chapter is limited to the use of remote sensing and map data for the estimation of area, although not all area information is obtained from these data. It is sometimes partially or even entirely provided by field measurements and observations.

Conventional aerial photographs have in the past been the only remote sensing tool used in forest inventory, and will certainly remain the most important one for a long time. The first part of this chapter will restrict the study of remote sensing in forest inventory to that of conventional aerial photographs, but sub-chapter 6 will be devoted to a description and present applications to forest inventory of the new remote sensing tools.

We will assume in this chapter that good topographic (or only planimetric) mapping over the whole area exists at a suitable(1) scale, permitting the reduction to a negligible value of the error on the estimate of the total area to be inventoried. If this is not the case, and if the inventory to be made is not a broad reconnaissance survey or does not apply to a relatively small area which can be topographically surveyed on the ground, the first objective of the inventory should be to have this mapping done from the existing remote sensing imagery by a cartographic institute using plotters of the first order. We will not study this technique nor the topographical survey methods which are well described in relevant manuals and textbooks.

In case this topographic mapping is not possible for financial or other reasons it must be pointed out that the resulting error over the total area will increase the errors on the estimates of the total volumes (or totals of other parameters).

(1) "Suitable" in relation to the size of the area to be inventoried and the intensity of the inventory work.

2 Forest and land-use classifications

21 Various kinds of classifications

Given a forested area to be inventoried, results of the inventory usually have to be given not only for the whole area, but also for parts of it. When dividing the inventoried area several simultaneous criteria may be used. Broadly speaking they are the following:

- Criteria of vegetation/environment relationships taking into account environmental factors such as climate, altitude and soils. The corresponding classification does not generally indicate the existing land-use, but is useful for land and forest management: decisions on whether to maintain the forest or clear it for agriculture, on location and species for reforestation, on silvicultural treatments, etc. can be made with greater confidence from information gathered through this classification.

- Criterion of present land use: this criterion defines the most important classification as it separates the forests from other land uses and vegetation types. In this classification the forest areas are broken down into very broad and universally accepted classes.

- Criteria of forest management: under this heading we include all the factors which are of direct relevance for forest management such as:

  - ownership and tenure; for instance, if there are publicly and privately owned forests in the inventoried area it is almost certain that it will be necessary to give separate results for each type of forest. The same occurs if there are forests under concessions which need to be separated from the other forests;

  - administration: results may have to be given by administrative units (districts, counties, regions, departments, provinces and states) if the inventoried area is spread over several such units;

  - physiography and accessibility: results will have to be given by isolated forest unit, by watershed, by type of relief, etc.... the corresponding units having to be managed separately;

  - management units: in addition to the foregoing there may be another management and/or logging classification (sustained yield unit, logging compartment, etc.). For instance, the classification into unexploited forests and logged-over forests is of primary importance in many tropical zones for the preparation of harvesting regulations. Results have to be given separately for each class.

- Criteria for statistical stratification: if in the same management and/or "present land use" and/or "potential land capability" unit forests are significantly different with regard to the parameters to be estimated, it is useful to stratify the forests accordingly in order to decrease the sampling error on the estimates and make the inventory more efficient. Stratification will be more efficient if it is done prior to sampling (see paragraph 411.4 of Chapter III). This stratification is generally done through photointerpretation and is based on criteria which can be appraised from aerial photographs, such as dominant species or height and density of the dominant trees. Classes based on the latter criteria are often called "condition classes". Results by condition class may not be useful since condition classes are in principle only strata used for sampling. But they are useful if this stratification is then used as a basis for management purposes.

22 Classifications based on vegetation/environment relationships

In most cases this type of classification is not used for assessing the present land use pattern as this pattern differs generally from the one of the potential or climax vegetation types which are considered in these classifications. However, they may be used in forest inventory for a primary broad stratification of the forests to be inventoried, especially when original vegetation has been more or less untouched.

Many systems of classification and mapping based on vegetation/environmental relationships have been evolved, some on a world basis, others on a more restricted regional basis, e.g. for Africa, Southeast Asia, and South America. They generally use various methods of analysis of the complex of factors making up the environment, with emphasis chiefly on one or more climatic factors, e.g. rainfall, temperature, evapotranspiration, etc. For the purpose of the forest inventory, it is necessary for the expert first to familiarize himself with a national classification system adopted for local usage, and relate this as far as possible to a suitable (1) regional and (2) world type classification.

It is not intended in this manual to consider the merits or limitations of the various world and regional classifications. It is advisable first to find out for each inventory project what vegetation/climatic maps already exist on a country and regional basis. Several maps have been published on world and regional classification systems, and some of the more recent may be mentioned:

1. Vegetation map of Africa, published under the auspices of the "Association pour l'étude taxonomique de la flore d'Afrique tropicale" with the assistance of UNESCO, by the Oxford University Press, 1958.

2. Atlas of maps of the "Crop Ecologic Survey in West Africa", by J. Papadakis under the auspices of FAO in 1966 (which includes also a classification of climatic zones correlated with vegetation types).

3. A series of maps for individual countries in Southeast Asia, Africa and Europe, published by Gaussen and his co-workers, e.g. publications of the Institut Français de Pondichéry covering India, Ceylon and Madagascar among others.

4. World climatic maps on the systems of Thornthwaite, Swain and Köppen.

5. Climatic vegetation maps for Latin America by Holdridge.

6. World vegetation map by Schmithüsen at 1/25,000,000.

UNESCO, the World Meteorological Organization (WMO) and FAO have been specially interested in, and have sponsored, the preparation of world or regional maps on specialized ecological aspects (including soils), e.g. the Crop Ecological Map of Papadakis referred to above, a study of the "Agroclimatology of the Semi-Arid Areas South of the Sahara in West Africa", by J. Cochemé and P. Franquin, jointly published in 1967 by FAO, UNESCO and WMO, and a World Soils Map by FAO to be completed in 1974. Though FAO has not yet specifically recommended any one system for a classification of vegetation on a world or regional basis, the Holdridge System appears to be of special interest both for its simplicity and easy adoption for forest inventory purposes. A description of this system is given by Holdridge (1967). This sytem has been applied to the compilation of ecological maps in several countries of Latin America.

23 "Existing land use" classification used by FAO inventory operations.

231 An area classification scheme was devised at FAO Headquarters at a meeting of forest inventory experts in September 1967 and FAO inventory projects have been asked to use it (with eventual introduction of sub-divisions to satisfy individual project requirements). In the preparation of this classification efforts were made to conform to the categories and definitions used by FAO in its World Forest Inventory compilation. The elaboration of world, regional and national statistics on forest resources will be more easily obtained as more agencies accept this classification.

The steps in the classification and the definitions and explanations required are as follows:

	Classification steps	Definition or explanation, if required
1.	Classify the area into: I. Land area II. Water area	The basis for this division should be defined and the date given, e.g. according to existing cartography, aerial photography, etc. Mangrove and coastal palm forests are to be assigned to "land".
2.	Classify "Land Area" into: A. Forest Area B. Other Wooded Area C. Non-Forest Area	Consider as forests: all lands with a "forest cover" (including natural bamboo and palm); i.e., with trees whose crowns cover more than 20% of the area, and not used primarily for purposes other than forestry. For the definition of a tree use the following one given by the "Terminology of forest science, technology, practice and products" (edited by F.C. Ford Robertson and authorized by the joint FAO/IUFRO Committee on Forestry Bibliography and Terminology): tree: "a woody perennial plant typically large and with a single well-defined stem carrying a more or less definite crown" Include: (a) Public and private forests; (b) All plantations, including one-rotation plantation, primarily used for forestry purposes; (c) Areas temporarily unstocked as well as young natural stands and all plantations established for forestry purposes, which have not yet reached a crown density of more than 20%; (d) Forest roads and streams and other small open areas, as well as forest nurseries, that constitute an integral part of the forest and which cannot be readily excluded by the survey system used. Exclude: (a) Isolated tree groups smaller than 0.5 ha; (b) City parks, private gardens and pastures; (c) Areas of windbreak and shelterbelt trees with an area exceeding 0.5 ha, but too narrow to be managed as forests.

	Classification steps	Definition of explanation, if required
2.	(contd.)	Consider as other wooded areas land with trees whose crowns cover less than 20% of the area or with shrubs or stunted trees covering more than 20% of the area, not primarily used for agricultural or other non-forestry purposes (such as grazing of domestic animals). Also include areas occupied by trees in lines (along roads, canals and streams, etc., converted to area by 0.8 ha per 1,000 m) as well as windbreaks and shelterbelts which are not included in "Forests".
3.	Classify the "Forest Area" into: 1. Natural Forests 2. Man-Made Forests	The differentiation between natural and man-made forests should be made on the basis of the classification given in paragraph 233.
4.	Classify "Natural Forests" into: (a) Broadleaved species excluding mangrove forests (b) Coniferous species (c) Mixed broadleaved and coniferous species (d) Pure bamboo areas (e) Mangrove (f) Coastal and riverine palm forest (g) Temporarily unstocked areas	Categories (a) and (b) will be defined by a composition of 80% or more of the species groups. Mixed forests with less than 80% of (a) or (b) will be classified as (c). Where bamboo occurs in the above types as understorey, this should be recorded to estimate mixed bamboo area. It may be useful to subdivide (a) into mixed broadleaved forests and pure (or almost pure) broadleaved forests in certain tropical areas where pure or almost pure stands of a broadleaved species occur (case of Gilbertiodendron dewevrei in Congo basin). Shifting cultivation areas already re-stocked with forest vegetation should be classified as sub-divisions of categories (a), (b) or (c).
5.	Classify "Man-Made Forests" into those applicable divisions shown under Step 4.	
6.	Classify "Other Wooded Area" into: 1. Savannah, open woodlands 2. Heath, stunted and scrub forest 3. Trees in lines, windbreaks and shelterbelts 4. Other areas	Savannahs should be considered as areas of scattered trees or scrub over graminaceous or herbaceous layer. Crown cover of the woody vegetation can exceed 20%. Categories (2) and (3) are defined under Step 2.
7.	Classify the "Non-Forest Area" into: 1. Agricultural land a. Crops and improved pastures	(a) includes shifting cultivation areas where land is under preparation for agricultural cropping, or is planted with agricultural crop or is not re-stocked yet with forest vegetation.
	b. Plantations	Plantations include orchards, rubber, palms, etc.

Classification steps	Definition or explanation, if required
(contd.)	
2. Other lands	
a. Barren land	E.g. rock, sand, ice, etc.
b. Natural range lands and grasslands	E.g. prairies, pampas, steppes. If a scattered layer of woody vegetation exists, the area should be classified in "other wooded areas".
c. Swamps	This includes swampy areas without a tree cover.
d. Heath without trees	E.g. tundra in northern zones.
e. Urban, industrial and communication areas	Includes rights of way for roads, railroads, power lines, etc.
f. Other areas	

232 FAO's proposed classification is, thus, the following:

Existing Land-Use and Forest Classes

I. Total Land Area

A. Forest area

1. Natural forests

a. Broadleaved excluding mangroves
b. Coniferous
c. Mixed broadleaved and coniferous
d. Pure bamboo
e. Mangrove
f. Coastal and riverine palms
g. Temporarily unstocked

2. Man-made forests

(those above divisions of a. to g. which are applicable)

B. Other wooded area

1. Savannah, open woodlands
2. Heath, stunted and scrub forest
3. Trees in lines, windbreaks and shelterbelts
4. Other areas

C. Non-forest area

1. Agricultural land

a. Crops and improved pastures
b. Plantations

2. Other lands

a. Barren
b. Natural range and grasslands
c. Swamp
d. Heath, tundra
e. Urban, industrial and communication
f. Other areas

233 Definition and interpretation of man-made forests

The following text is issued from the note "Actual and potential role of man-made forests in the changing world pattern of wood consumption" which was delivered by the Secretariat of the "World Symposium on man-made forests and their industrial importance" (Canberra, 14-25 April 1967).

"The phrase sounds simple enough but has caused difficulty in definition and differences in interpretation. In fact, certain of the natural distinctions between types are blurred and some degree of arbitrary definition is needed. Any final, authoritative definition must await the findings of the current Multilingual Forestry Terminology Project, which is working under the guidance of the joint FAO/IUFRO Committee on Bibliography and Terminology and with the comprehensive support of the U.S. Forest Service, the Department of Forestry in Canada, and the Society of American Foresters. Meanwhile, some guidance is available from the definitions adopted by the second session of the European Forestry Commission's Working Party on Afforestation and Reforestation (1953), as amended by its third session (1954), as well as existing terminologies such as "British Commonwealth Forest Terminology, Part I" and the Society of American Foresters' "Forestry Terminology".

It seems simplest to equate the definition of a man-made forest with that given for a plantation in the BC Forest Terminology, i.e.: "A forest crop raised artificially, either by sowing or planting". This could be interpreted to include all forms of artificial regeneration but no natural regeneration. "To regenerate" in English is normally defined as "to cause to be born again, to re-create", which implies the renewal of something pre-existing rather than its replacement by something different. In this sense, a forest formed by artificial regeneration can be said to be re-made by man rather than made by man.

The different types of forest, according to their means of origin, are:

1. Those established artifically by afforestation on land which previously did not carry forest. This is the most clear-cut example of a man-made forest and invariably involves the extension of the area of the forest. A clear definition of the period of time for which the land previously carried no forest is needed. "Within living memory" is suitable for areas where there are no records, but "within 50 years" is suggested as an alternative for areas where records exist.

2. Those established artificially by reforestation on land which carried forest within the previous 50 years or within living memory, and involving the replacement of the previous crop by a new and essentially different crop. The change most frequently involved is species conversion, but the use of seed known to be genetically different from the previous crop, e.g. from seed orchards consisting of superior genotypes demonstrated by progeny trials, would also qualify. Inasmuch as the forest established artifically by man is essentially different from its predecessor, this too is a clear-cut example of a man-made forest, though it does not involve any change in forest areas. The term "reforestation", it is suggested, should be confined to this type, to distinguish it from the following.

3. Those established by artifical regeneration on land which carried forest within the previous 50 years or within living memory, and involving the renewal of what is essentially the same crop as before. Inasmuch as the new crop is essentially the same as its predecessor, this is a forest re-made, rather than made, by man.

4. Those established by natural regeneration, with deliberate silvicultural assistance from man. In the past, such assistance has sometimes cost more in time, effort and money than certain of the cheaper forms of artifical regeneration. Nevertheless, inasmuch as the source of seed or vegetative reproduction is natural, it seems logical to consider this as natural (but man-assisted) forest.

5. Those established by natural regeneration without deliberate assistance from man. They would include so-called "Virgin Forests", as well as those regenerated by wholly natural means. They are the most clear-cut examples of a Natural Forest.

The definition included in the questionnaire distributed to countries attempted to draw the line between number (2) and (3) of the above types, in order to include as man-made forests all those which involved the creation of something essentially new but to exclude those which are formed by renewal of the same type of forest as before. This seemed a logical distinction and was in line with that made by the European Forestry Commission's Working Party on Afforestation and Reforestation, when it defined artificial regeneration as: "Restoration of forest cover by planting or sowing in the normal course of management", and reforestation as: "Restoration of forest cover by planting or sowing, when it has not been possible to effect this restoration in the normal course of management". Some difficulties, however, have arisen in interpretation. Borderline cases may arise in which it is difficult to determine whether the specific composition of the new forest is or is not essentially the same as that of the previous crop, or whether the management methods in use are normal or not. It seems preferable, therefore, to draw the line between 3 and 4 and to include within the term "man-made" all forms of artificial regeneration. This agrees exactly with the existing simple definition of a "Plantation" in the British Commonwealth Forestry Terminology - "A forest crop raised artificially either by sowing or planting."

Mixed regeneration systems. - Difficulty arises when both natural and artifical regeneration are carried out in the same area. In such cases it is proposed that the deciding factor should be the intended composition of the final crop. If over 50% of the intended final crop has been regenerated artificially, the forest should be considered as man-made.

Shape. - "Forest implies width as well as length and can scarcely be applied to row plantations. Likewise "forest crops" implies that a high proportion of the trees are growing in competition with each other in the "crop" rather than with other forms of vegetation outside it and are thus capable of forming a true forest environment. Row plantations, avenues, etc., in which a high proportion of the trees are subject to edge effect, do not conform to this description. Though unquestionably man-made, they are not strictly forests. Wide shelterbelts of a kilometre or so wide, like the "green belt" at Khartoum, on the other hand, equally definitely are. It is thought that a 100 m width should be the minimum to constitute a forest. In practice, the importance of row plantations and shelter-belts in many countries often makes it essential that they be considered together with more orthodox shapes of man-made forests, as will be done in the present symposium, but they should be mentioned explicitly. It should be noted that the European Forestry Commission's Working Party on Afforestation and Reforestation defined "Plantations outside the Forest" as "Row plantations (road-side planting, windbreaks, etc.) and plantations in stands associated with a permanent agricultural revenue on the same site".

Stocking. - "Forest" implies a closed canopy, at least when the trees are old enough to form one, and hence a certain minimum stocking. This needs to be specified strictly in order to avoid the fallacious inflation of figures for areas "afforested" by the inclusion of "plantations" only 10% stocked and largely

incapable of making full use of the productive capacity of the site. It is proposed that for young crops not yet thinned, full stocking should mean a minimum of 1,000 stem/ha or 75% of the trees planted, whichever is the less, with a reasonably uniform distribution. Plantations with 25-75% survival or 300 to 1,000 stems/ha should be considered as partially stocked and those with less than 25% survival or less than 300 stems/ha as poorly stocked. The latter should, in many cases, be considered for writing off and complete replanting.

Naturalization. - Plantations of exotics are, ipso facto, man-made during the first rotation. If subsequent rotations are regenerated naturally, it is debatable whether the forests so formed should be called natural on account of their method of regeneration or man-made because they could never exist had it not been for man's active intervention through the initial introduction. In such cases it is necessary to have recourse to a purely arbitrary definition; it is suggested that naturally regenerated crops of exotics should be considered as "man-made forests" up to 250 years from the date of their original introduction into that area, but that after 250 years the species should be considered as naturalized, when only artifically raised crops could be considered as man-made.

Agricultural v. forestry crops. - The logic of the distinction between agricultural tree crops and forestry tree crops is often obscure. There seems no good reason, for example, why plantations of rubber trees are thought of as an agricultural crop, while plantations of tan-bark acacia trees are classed as a forest crop. It is pointless to try to change distinctions which are now generally accepted by tradition, but it is important to ensure either conformity between countries in the species included in man-made forests for which area figures are cited, and those excluded as being "agricultural crops", or at least a knowledge of the differences. As an example, Ivory Coast has included over 5,000 hectares of Anacardium in its man-made forests, whereas in other countries this may be considered an agricultural crop."

3 Interpretation of conventional aerial photographs in forest inventory

31 Introduction

311 Area estimation with or without forest mapping. The use of all the classifications listed in paragraph 21 leads to a distribution of the total area in sub-divisions or strata. One objective of a forest inventory is to get satisfactory estimates of these areas (or of the proportions of these areas with respect to the total area). In many cases an additional objective of a forest inventory is to know the exact location of these areas by a delineation on a map.

312 "Compulsory" classifications and classifications developed within the inventory. The classifications listed above are of two sorts:

(a) Some existing classifications are already given and cannot be avoided or amended by the inventory expert. This is the case, for instance, of the ownership and administrative classifications. Estimation and mapping of the areas of the corresponding classes do not generally require interpretation of aerial photographs: they consist mainly in transferring onto the available topographic (or planimetric) maps information obtained from existing documentation (such as laws creating forest reserves, concession agreements, etc.), and in measuring areas on these maps. Aerial photographs may be used occasionally to add to the maps some missing details referred to in the relevant documentation (planimetric or topographic features such as a small river, the ridge of a range of hills, etc.).

(b) Some other classifications are set up partly or entirely by the inventory officer, e.g. classifications of present land-use, of accessibility, of "condition classes". But the inventory officer must try as far as possible to fit his classifications with existing and well-accepted ones, so as to allow for comparison and addition of results given by different inventories designed by different foresters. Unfortunately this is not very often the case and too many inventory operations develop their own classifications, disregarding the existing ones. If former classifications are not deemed satisfactory one should first try to refine or to condense them in order that classes (or groups of classes) of his own classification are compatible with classes (or groups of classes) of an existing one. Only if this attempt proves unsuccessful will a new classification be made.

Estimation and delineation of the areas corresponding to these classifications are made generally through interpretation of aerial photographs.

32 Some information on aerial photographs and aerial coverages

(Many textbooks and manuals exist on aerial photography and photointerpretation. Some of them are listed in the bibliography, and it is not intended to review or even to summarize in the following paragraphs all relevant information, but more simply to point out the most important elements for inventory officers using conventional aerial photography.)

321 Characteristics of aerial photographs

321.1 Scale

321.11 Definition

The scale (or representative fraction) is the relationship between a distance on the photographs and the corresponding distance on the ground expressed as a fraction (1/25,000) or as a ratio (1:25,000): 1 cm on aerial photograph is equivalent to 250,000 cm = 250 m on ground.

It is equal to the ratio: $\frac{\text{focal length of the camera}}{\text{altitude of the camera above the ground}} = \frac{f}{H}$

H is exactly the distance between the lens of the camera and its vertical projection on the ground.

If the terrain is not completely flat the scale is not uniform all over a given photograph. This is particularly important when the scale is relatively large (relatively low average altitude) and the terrain is mountainous (significant differences between altitudes of various points of the terrain).

321.12 Suitable scales for forest inventory (scale requirements for forest inventory)

A classification of scales of aerial photographs can be the following:

1/200 to 1/3,000	very large-scale aerial photographs
1/3,000 to 1/10,000	large-scale aerial photographs
1/10,000 to 1/25,000	medium-scale aerial photographs
1/25,000 and smaller	small-scale aerial photographs

The large or very large aerial photographs are used in forest inventories in which estimation of the stand parameters is carried out mainly through measurements on the photographs (photogrammetry). This is the case in some temperate forests with a limited number of recognizable species, parameters measured being the height of dominant and co-dominant trees, the density of the crown cover, the diameters of the individual crowns, etc. One of the problems to be solved is the precise estimation of the elevation of the camera above the ground (useful in its turn for obtaining a precise estimate of the scale of the photographs).

The medium and small scales are generally used only for stratifying, mapping and estimating the forest areas in forest inventories where all or most of the parameters are estimated through field work. The most suitable scale in each forest inventory depends much on the refinement of the stratification to be made and on the criteria used for this stratification. For instance, if individual species must be recognized, a medium scale may be necessary. But if the stratification does not imply the recognition of individual species, a smaller scale may suffice. This happens very often in mixed tropical forests in which identification of individual species is generally not feasible at present, at least at scales smaller than 1/10,000 and therefore is not used as a criterion for stratification.

In many tropical countries the only photographs available have a small scale since aerial surveys are primarily designed for topographic mapping at a scale generally not larger than 1/50,000.

The following table roughly summarizes the use of the various scales of aerial photographs for forest inventory:

Type	Scale	Uses
Very large scale Large scale	1/200 - 1/3,000 1/3,000 - 1/10,000	Photogrammetric measurements (stand parameters estimation) or refined stratification based on quantitatively measured criteria
Medium scale	1/10,000 - 1/25,000	Broader stratification based on qualitative criteria including species occurrence or on estimated quantitative criteria (such as crown density or height of dominant trees)
Small scale	$<$ 1/25,000	Broad stratification based on qualitative criteria excluding in most cases species occurrence and on broad classes of quantitative criteria

321.2 Type of emulsion

Conventional aerial photographs are images of the reflexion by the objects of the electromagnetic radiations of the visible spectrum ($0.4\mu - 0.8\mu$) with the possible addition of those of the near infra-red (up to 1μ). In the latter case the photographs are called infra-red photographs.

321.21 Conventional photographs without the near infra-red

Panchromatic black and white photographs are the most common and most used up to now. In fact most of the extensive aerial surveys for topographic mapping use panchromatic films. They are also the ones which most people are more accustomed to. The spectral sensitivity of most of the aerial panchromatic films ranges between 0.36μ and 0.72μ. In many cases they are used with a minus blue filter to cut off blue light below 0.5μ. Resolution (in terms of lines per millimetre recorded by the film), speed and grain vary considerably from one film to another.

Colour aerial photographs are much less common and are generally used for special purposes on limited areas. They are now only a little more expensive than the corresponding panchromatic photographs. It is said that "the human eye can separate more than 100 times more colour combinations (hues, values and chromas) than gray scale values (ratio of 20,000 to 200)". Species identification as well as detection of diseased stands is easier on colour aerial photographs than on panchromatic ones so that a more refined stratification is generally feasible.

321.22 "Infra-red" photographs

The sensitivity of infra-red black and white films extends to 0.9μ or 1.0μ. Filters generally cut out the blue and blue-green wavelengths, so that the range of sensitivity is approximately from 0.6μ to 0.9μ. The main differences for forestry interpretation between the black and white film and the infra-red one are the following:

- easier distinction on infra-red photographs between angiosperms (broadleaved species) and gymnosperms (coniferous);

- possible distinction between healthy and diseased broadleaved trees on infra-red photographs;

- easy differenciation on infra-red photographs between water areas and land areas, and between wet and dry soils: this is particularly useful for the delineation between forest on dry soils and swamp forests;

- better individualization of the trees on the infra-red photographs than on the panchromatic ones; consequently it is easier to delineate the stands on panchromatic photographs. This is especially true on large scales.

The colour infra-red films ("false-colour" film or Russian "spectrozonal" film) allow for the reproduction in colour of the same spectral range as the infra-red black and white film. It combines the advantages of the colour reproduction (large number of combination of hues, values and chromas) and those of sensing the near infra-red (detection of humidity and of stress of vegetation). Identification of species, and more generally refined stratifications based on soil moisture, stand composition and vegetation health is easier on this type of film than on the three former ones.

Colour additive viewing makes possible a large number of different falsecolour pictures from the same set of one-band photographs (see paragraph 613 of this chapter).

321.3 Printing

Prints (on opaque or transparent mediums) are made from negatives by contact printing or automatic dodging printers. The latter is more economic and "has the advantage of accommodating on one print the range of densities occurring on the negative".(1)

(1) from J.A. Howard, "Aerial photo-ecology", pages 36-37.

"Glossy prints with a high contrast have the advantage of a greater density range but matt prints can easily be written on and the reflected glare from the surface is not so trying to the eyes. Nowadays a semi-matt or semi-glossy or glossy-matt surface is generally preferred as a compromise between the two types". (1) The possible defects of aerial prints are numerous and provision must be made in the contracts of aerial surveying in order to avoid them as much as possible. They are listed in the book referred to in (1): blurred areas, fingerprints, abrasion streaks and scratches, air belts, fog, streaks, irregular white spots, irregular dark spots, flat prints, excessive contrast (see below), density too high or too low, blisters, brown spots, bellow stain, fading, double image, drying marks, pressure-bar marks, fork-like or finger patterns, dark streaks, small over-exposed circular zone.

321.4 Basic image quality factors

The interpretation of the aerial photographs depends on the ability of the interpreter, on the equipment used and also of course on the qualities of the photographs. These qualities can be estimated from the following three main factors:

- tone contrast (or colour contrast for colour photography) which can be defined as "the actual difference in photographic tone or brightness between a particular feature that is to be interpreted and the background against which it is imaged";

- "sharpness" which corresponds to "the abruptness with which a change appears to occur on the photograph": the sharper the photograph, the easier the interpretation;

- "stereoscopic parallax" which means "the difference in the apparent position of one feature - such as the top of a tree - with respect to another feature - such as the base of that tree - caused by a shift in the point of observation". It is measured by the parallax difference Dp, and is related to the difference in elevation h of these two features by the following formula:

$$h = \frac{H \times Dp}{P}$$

  where H is the height of the camera above the ground and P is the "air base", viz. the horizontal distance between the two points of observation; Dp being expressed as the sum of the projections parallel to the flight line on each photograph of the distances between the two features. This formula is used in photogrammetry for measurement on the photographs of such things as tree height. A measuring instrument based on this formula is the parallax bar; a simpler device is the parallax wedge.

322.1 Overlaps

Along the same flight line, the areas covered by two successive photographs are overlapping. This overlap can be expressed as a percentage of the area covered by one photograph and is called "forward lap" (or endlap). The "side lap" corresponds to the overlap between photographs in adjacent parallel flights.

Forward lap is usually between 55% to 65%, and side lap is more variable, from 10% to 40% or more. Both overlaps are necessary for good stereoscopic interpretation and plotting for mapping of the surveyed area.

(1) from J.A. Howard, "Aerial photo-ecology", pages 36-37.

The number N of photographs corresponding to the aerial coverage of a given area S is approximately equal to:

$$N = \frac{S \times e^2}{1^2(1-R_1)(1-R_2)}$$

where e is the average scale of the aerial survey

l is the side of an aerial photograph

R_1 is the forward lap (usually $0.55 < R_1 < 0.65$)

R_2 is the side lap (usually $R_2 > 0.10$)

(if S is expressed in ha, l must be expressed in hm)

For instance, let us suppose that:

$S = 1,000,000$ ha

$e = \frac{1}{20,000}$

$l = 23$ cm $= 0,0023$ hm (9 inches)

$R_1 = 0.60$

$R_2 = 0.20$

We will have:

$$N = 1,000,000 \times \left(\frac{1}{20,000}\right)^2 \times \frac{1}{(0.0023)^2 \times 0.40 \times 0.80} \# 1,500$$

Graphs can be constructed on which it is possible to read N for a given scale, assuming given overlaps and size of the photographs.

Due to significant variations of scales in mountainous areas it is adviseable to request larger endlaps (up to 80%) and sidelaps (up to 40%).

322.2 Flight lines

Flight lines should be theoretically parallel and equidistant. Due to many factors such as crabbing and drift of the flight, tilt and tip of the aircraft, the overlaps are not constant.

Flight indices on stable transparent medium, where the flight lines are drawn with the indication of the centre of the successive photographs, are very useful and must be requested in any aerial survey contract.

322.3 Tilt and rectification

Tilt and tip of the aircraft result in the camera tilt which is equal to the inclination of camera axis with respect to the vertical. Thus the plane of the photograph is not exactly horizontal. The tilted photographs can be rectified, i.e. projected onto a horizontal reference plane, the angle between the photograph plane and the horizontal being determined by ground reconnaissance or from flight data.

322.4 Other specifications

Annex I refers to other specifications of aerial surveys such as junction of strips (important when the aerial coverage if obtained from several flights or when it is to be used in combination with other surveys covering neighbouring areas), cloud cover (which must be less than a given percentage), time of day - shadows must not reduce the value of the photographs for interpretation.

323 Some problems related to aerial surveying. In many forest inventories it is desirable to get new aerial photographs because they are missing on a part or on the whole area to be inventoried, or because they are too old (in case there have been rapid changes in land use since the date of the former coverage) or because they do not have the suitable scale or characteristics. If money is available and if the inventory design includes the use of aerial photographs, aerial surveying will have to be contemplated.

In addition to the technical specifications which are listed in Annex I, some other points have to be considered when preparing a contract of aerial surveying.

(a) Government restrictions:

Many governments exercise varying degrees of restriction over the execution of aerial photography. It is necessary to investigate whether the aerial surveying is permitted over the inventoried area (in particular by foreign contractors), if the processing is permitted outside the country (when the local processing facilities do not meet with the technical specifications), etc.

(b) Preliminary information to be collected:

In order to enable an invitation to bid to be issued, investigation has to be made on such items as:

- flying season, number of likely photographic days and general meteorological information;
- topography, terrain and altitudes in area to be photographed;
- existing documentation (maps) and ground control;
- location of airports with servicing facilities
- permits required, etc...

(c) Cost and payment:

The cost of an aerial survey is not only determined by the size of the area to be inventoried for given scale and characteristics of the photographs. Positioning (mobilization and demobilization) and stand-by may have an important bearing, especially in tropical countries where the cloud cover is often a serious inconvenience. The basis for payment may be photography only; photography plus positioning; photography, positioning and standby; photography, positioning, standby and flying hours, or various combinations. It is a matter of weighing the various components, when bids are received, in an attempt to ensure that photography will be obtained at a reasonable price.

The example below shows the range of costs per item according to the relative importance given to them by the tenderers. It is related to a survey made in 1972 at various scales within an area of 5,000 km^2 in a tropical country.

		Bids (in US $)
1.	Mobilization	1,200 to 6,150
2.	Demobilization	1,200 to 6,150
	Sub-total (positioning)	2,400 to 12,300
3.	Rate per km^2 for 1/15,000 panchromatic photography	4.73 to 7.98
4.	Rate per km^2 for 1/30,000 infrared photography	3.42 to 6.77
5.	Rate per km^2 for 1/5,000 panchromatic photography	24.47 to 37.31
6.	Rate per km^2 for semi-matt contact prints from 3 above	
	(a) first set	0.17 to 0.75
	(b) second set	0.13 to 0.35
	(c) subsequent sets up to 6	0.13 to 0.30
7.	Rate per km^2 for semi-matt contact prints from 4 above	
	(a) first set	0.09 to 0.26
	(b) second set	0.07 to 0.15
	(c) subsequent sets up to 6	0.05 to 0.15
8.	Rate per km^2 for semi-matt contact prints from 5 above	
	a) first set	3.00 to 5.71
	b) second set	1.60 to 3.00
	c) subsequent sets up to 6	1.53 to 3.00
9.	Rate for map photo indices of the photography in 3 above (indication of the indices on existing 1/50,000 topographic maps)	0.10 to 26.64
10.	Rate for map photo indices of the photography in 4 above	0.10 to 1.21
11.	Rate for map photo indices in the photography in 5 above	1.50 to 61.35
12.	Rate per km^2 for the production of an uncontrolled mosaic at a scale of 1/15,000 from the photography in 3 above including a screen positive of each set	1.41 to 3.66

324 Mosaics. It is sometimes useful to use an assemblage of the aerial photographs in order to get a clear picture of the inventoried area or of parts of it. This assemblage may be "composed of uncorrected prints, the detail of which being matched from print to print without ground control or other orientation" and the mosaic is said to be uncontrolled. A controlled mosaic is made up of prints which have been rectified and ratioed (in order that all the photographs have the same average scale). Semi-controlled mosaics are made up of corrected or uncorrected photographs arranged through "a common basis of orientation other than ground control".

Controlled mosaics are not yet comparable to a map as variations for lens aberrations and displacement due to topography are not corrected. The completely corrected mosaics are the orthophoto-mosaics called also "orthophotomaps" (see paragraph 614 of this chapter). However, in flat or gently undulating terrain controlled mosaics can be used as planimetric maps.

33 Photointerpretation

Photointerpretation in forest inventory consists in the identification on the aerial photographs and eventually in the delineation of the different classes corresponding to the classifications adopted.

Some classes within the inventoried area are relatively easy to identify and delineate, as they are defined by geographical limits, such as classes corresponding to ownership, tenure, administration or physiography. The most important and most interesting part of the photointerpretation work in forest inventory is related to the identification (and eventually delineation) of the various classes of land use, vegetation, forest type and accessibility.

331 Qualities of good photointerpretation. A good photointerpretation must be as objective as possible. Although the analysis of the aerial photographs is made through direct observation and interpretation by a human being, it should always be based on a set of precise criteria and definitions or keys. This requirement is necessary for the following two main reasons:

- photointerpretation must be as uniform as possible over time from the beginning to the end of the work; the keys thus serve as a permanent reference to the photointerpreter;

- photointerpretation must be as consistent as possible regardless of the photointerpreters and the keys will serve to reduce the discrepancies between them. These keys also serve as an aid for the field teams in on-the-spot recognition of the different photointerpretation classes and thus make it easier to match the photointerpretation and field classifications.

The criteria for the classifications used in photointerpretation must be easily identifiable on the ground in order that they can also be used in the field inventory. In other words, classifications designed on the basis of photography parameters such as crown cover, height of dominant trees, soil moisture, topographic features, should be meaningful and acceptable for a person on the ground; otherwise they are useless for the inventory. In many inventories the photointerpretation work and the field inventory have been done independently, with the result that the photointerpretation work used for forest mapping has not served to reduce the sampling error of the inventory results and conversely these results could not be applied to the individual forest classes delineated on the maps. It may happen that changes in the forest cover since the taking of the aerial photographs, or errors in the photointerpretation work, introduce some discrepancies between the results of the photointerpretation work and the field work. These discrepancies can be taken into account in the inventory design (see chapter 7) provided the classifications of the forest areas used in the photointerpretation work and in the field are basically the same.

As a consequence of the above requirements (objectivity and feasibility for use in the field), the photointerpretation classifications must not be too refined. If they are, the risks of errors, of inconsistencies over time and between interpreters, and of discrepancies with the field observations, are increased and consequently result in a poor performance.

332 Stereoscopic interpretation. Interpretation of conventional aerial photographs should always be made stereoscopically in order to profit from the perception of height which, according to many specialists, should be considered one of the most effective components of the interpretation. Observation of single photographs and of mosaics may, of course, provide useful information, but to a lesser degree.

Stereoscopes can be classified in three categories: lens stereoscopes, mirror stereoscopes, and special application stereoscopes.

Lens stereoscopes are generally small instruments with magnifying (2 to 4) lenses separated by a distance equal to the spacing of the eyes. They can be used easily in the field, but have drawbacks such as limited magnifying power, the impossibility of viewing the entire stereoscopic area in the line of flight without raising the edge of one of the photographs, and the impossibility of viewing the entire stereoscopic area across the line of flight without shifting the stereoscope or photographs.

Mirror stereoscopes use a combination of prisms, mirrors and lenses to avoid the above-mentioned defects of the lens stereoscopes. They are the basic instruments of photointerpretation in the office. Different types of frame make it possible to scan the whole area with high magnification, either by moving the plate on which the photographs are put, or by moving the whole optical set, or only the mirrors ("Old Delft" scanning stereoscope).

Of the special application stereoscopes, one has been designed to allow for the stereoscopic viewing of several successive photographs of the same flight strip; another has been designed for training purposes and permits simultaneous viewing of the same photographs by two interpreters.

333 Assessment of photointerpretation keys. The preparation of photointerpretation keys should always be considered an important part of the photointerpretation work, and sufficient time should be spent on it. As it is essential that the photointerpretation classification be easily utilizable in the field, many ground checks have to be carried out on the different vegetation and forest types. A key should always be supported by a set of test stereogrammes, each class being illustrated by one or more stereogramme. If density of the crown cover is used as a criterion for stratification, "density scales" reproducing crown covers with different percentages of crown closure can be used.

334 Photointerpretation of plots and photointerpretation with delineation

334.1 Introduction

In a large-scale forest inventory, forest mapping may not be an objective of the operation and it may be sufficient to estimate the areas of the different classes of forest by a sampling of plots on the aerial photographs without delineating the classes on the photographs and without transferring the limits onto topographic or planimetric maps.

Photointerpretation of plots is generally more satisfactory than photointerpretation with delineation. As a matter of fact it is often difficult to draw an exact limit between classes; some subjectivity is unavoidable and there are transition zones between vegetation types or forest types. Photointerpretation by plots is less liable to subjectivity. Estimates of the area of the same forest type by the same photointerpreter may be significantly different under each of the two methods, and this difference will not be entirely due to the sampling design used for the photointerpretation by plots. It is preferable in many cases to accept a known sampling error on valid basic data (photointerpretation by plots) than to obtain area values not subject to sampling errors but subject to unknown subjective biases (photointerpretation with delineation).

334.2 Photointerpretation of plots

- In photointerpretation without delineation, plots of equal size should always be used rather than points, so that the assessment of the vegetation or forest type is always done on the same reference area. (In photointerpretation with delineation the assessment of the areas of the different classes can be made by dot counts on the photographs, or on the maps once information from the photographs has been transferred). The plots are

generally circular with a radius of two or more millimetres on a photograph. These circular plots are generally printed on a stable transparent material laid on each photograph. If the aerial coverage in an inventory is based on more than one scale, it is better to retain the plots at a constant size; thus, the circles printed on the transparent overlay will have to vary in size in accordance with the scale.

A plot is assigned to a given class if more than 50% of its area belongs to this class. The corresponding parameter for this class has the value 1 in this plot; 0 in a plot not assigned to this class. The proportion of the total area covered by a given photointerpretation class and the standard error are estimated by formulas given in paragraph 53 of this chapter.

- Sampling design.

In principle, the sampling of the plots to be interpreted should be made on a base map or on a mosaic, and the plots thus selected transferred onto the photographs. The layout may be random or systematic over the whole area to be inventoried, or over each stratum already delineated on the map (such as administrative or physiographic units).

For the sake of convenience the layout of the sampling plots is often made directly on the photographs. The effective area of one photograph is assumed to be a rectangle in the middle part, the sides of which are determined from the average endlap and sidelap of the photographic coverage. Plots are selected in each rectangle according to a systematic or random pattern. If the topography is even and the overlaps nearly constant, then a systematic distribution of the plots on each photograph will result approximately in a systematic distribution over the inventoried area.

Due to variations in scale and in overlaps, the sampling intensity - which is the same in each rectangle - varies from one photograph to the next. A correction factor has to be applied to all the plots of a given photograph (or group of photographs of approximately the same scale and having the same overlaps) to take into account these variations in sampling intensity when they are significant. (1)

A systematic or random sample of aerial photographs may be selected for interpretation instead of having all photographs interpreted. In this case the layout corresponds to a two-stage sampling design, the rectangular effective areas of the photographs being the primary units, and the plots the secondary units (estimation procedure may be the one described in paragraph 422.121.111 "estimation of a proportion", if the plots are not systematically distributed on each selected photograph).

334.3 Photointerpretation with delineation

When forest mapping is required, the various classes must be delineated on the photographs. The effective area of each photograph has first to be delineated and the delineation on this photograph restricted to the effective area. Detailed instructions have to specify the dimensions of the minimum patch to be delineated (in relation to the scales of both the photography and the final map), the precision of the delineation, and other items such as degree of illumination of the photographs under the stereoscope, type of pen or pencil to be used, rubbing out of the wrong lines, etc.

(1) Other more sophisticated methods of correction exist: one of them consists of determining the effective area of each photograph and using a correction factor related to the scale of the photograph.

4 Forest mapping from conventional aerial photographs

41 Introduction

Mapping is generally done once the interpretation of the aerial photographs and delineation on the photographs of the different forest and vegetation classes have been completed. This is necessarily the case when the mapping is done using non-stereoscopic plotters (see paragraph 42). When stereoplotters are used, it may be possible to do the photointerpretation and the transfer simultaneously since the operator has a stereoscopic view of the area to be mapped. Stereoplotters of the third order can be bought and used within the framework of an inventory operation, whereas stereoplotters of the first and second order are generally the property of photogrammetric companies and institutes.

As already stated in sub-chapter 1, we will assume that an acceptable planimetric or topographic mapping exists at a suitable scale over the whole inventoried area.

42 Transfer from single photographs

In this case the operator does not have a stereoscopic view of the area to be mapped during the transfer, since only one photograph is used at a given time. The stereoscopic interpretation is assumed to have been done before the mapping operation and cannot be checked and eventually corrected during the mapping; this is a serious shortcoming but on the other hand the equipment used is simpler and less expensive. The instruments must allow for adaptation of the scale of the photograph to that of the map to be drawn. Adjustment of the photograph must be possible around its centre in order to rectify the photograph, if necessary, to take into account the relief displacements and thus to put in optical coincidence the same terrain features on the photograph and on the map. To avoid too much manipulation of the photographs the transfer of the interpretation lines should be restricted to the central effective area of each photograph (see paragraph 334.3).

The usual instruments are based on the principle of the camera lucida and most of them are called sketchmasters (Zeiss Aerosketchmaster, Aero Service Universal and Vertical Sketchmasters, Abrams Oblique Sketchmaster). The following description of this type of instrument is extracted from the "Manual of Photographic Interpretation" of the American Society of Photogrammetry: "The observer perceives two superimposed images, one from the photograph and the other from the manuscript (map). This result is attained by means of a semi-transparent mirror which both reflects and transmits light. The eye receives the image of the manuscript by transmitted light. The operator can adjust the instrument so that selected images on the photograph coincide with their true positions on the manuscript. Most of the camera lucida instruments can be raised or lowered to change the scale and tilted to compensate for tilts in the photographs". The ratio of the scales of the photograph and of the map can generally be down to 1:3 or 1:4.

This type of instrument is particularly recommended for transfer from single photographs if the relief is not too broken and the strata not too small and not too intricate. If this is not the case it may be more efficient to make a visual transfer without the use of any instrument.

43 Transfer from stereoscopic pairs

The main advantage of this type of transfer over the use of single photographs is that it allows for a simultaneous photointerpretation, or for checks and possible corrections of the photointerpretation work if this has already been performed.

The simplest and most usual instruments belong to two groups.

- The Radial Line Stereoscopic Plotters (third order), such as the Kail Plotter or the Hilger and Watts Plotter, whose principle is the following: each point of the

terrain corresponds to the intersection of two lines, each one passing through the centre of one of the two photographs ("radial lines"): the two lines are moved in order to intersect at the points along a limit between forest classes, and a mechanism links their intersection, possibly through a pantograph, to a drawing pencil marking the reference map or manuscript. These instruments to not correct for tilt and are difficult to use for transfer of detail near the flight line.

- The Multiscope and the Hilger and Watts Stereosketch consist basically of a mirror stereoscope combined with a camera lucida. The photograph tables of the first instrument (or the drawing table of the second) can be tilted to rectify the photographic image and take into account the relief displacement. In addition, scales can be adjusted by inserting different lenses or moving up and down the drawing table (Stereosketch).

- More sophisticated stereoplotters using the principle of the fused floating dots (for instance a parallax bar) can be used, such as the Zeiss Stereopret or some stereoplotters of third order (Zeiss Stereotope or S.O.M. Stereoflex).

5 Area estimation from aerial photographs and maps

51 Introductory remarks

As already mentioned in paragraph 334, estimation of the areas of the different forest or vegetation classes does not require mapping of these areas; an objective estimation can be performed by allocating, through photointerpretation, every photoplot of a sample to its forest or vegetation class, provided the sampling design is sound and that correction factors are applied to take into account the possible variations in scale and in overlapping of the photographs.

Accuracy of the area results should be of the same order of magnitude as the total error (sampling and measurement errors) of these estimates: there is no point providing area results to the nearest hectare if the total error is expected to be around 100 hectares.

Area results should be given in the metric system whenever possible. If the British system is used, both British and metric units should be given, as is required in all inventories carried out by FAO.

Whatever method is used for estimating areas on maps, the precision of the estimation will be higher with larger scales. This shows the importance of transferring details of photographs onto maps at a scale which is not too much smaller than that of the photographs.

On a forest map, patches with dimensions smaller than a certain minimum are not shown. This provision is generally necessary to avoid difficulties in reading the map, but it may lead to biased estimations of some forest classes. The most obvious case of such bias is when a classification of forests is made according to the individual sise of forest patches, the area of the forest class corresponding to the smallest patches being underestimated. This problem must be kept in mind, particularly when estimating forest areas on small-scale maps.

A fundamental prerequisite for estimating areas on maps is that the maps must be drawn on a paper with a high dimensional stability coefficient. This is particularly true for maps drawn on tracing paper; ordinary commercial tracing paper can expand up to 15%. Many stable-based materials are readily available (with polyester base or estar base, the latter being less stable), and it is highly recommended that these be used for mapping in order to avoid considerable and unknown biases in the area estimation.

There are several ways of measuring areas on maps. The indications given below refer only to planimetering and to methods based on sampling techniques, since the other ones are deemed less practical in most cases (such as the one using geometric formulas and coordinates or the one based on weighting).

52 Direct measurements by planimetering on maps

Hand planimeters have been used for some time and now there exist the much more accurate and rapid electronic planimeters such as the Stanley Cintel Electronic Planimeter or the Kimoto Electronic Scanning Planimeter. In addition to the need for dimensionally stable paper, mentioned above, other precautions have to be taken, among which can be quoted the following:

(a) correct the scale setting given with the instrument against a master area generally provided with the instrument;

(b) check that the measuring wheel is parallel to the tracer arm;

(c) avoid any slipping of the measuring wheel during the measurement operation;

(d) perform a sufficient number of measurements in order to reduce the measurement error.

Unless an electronic planimeter is available, it is advisable to use statistical methods (especially the dot-grid system) as they are less liable to measurement errors and allow for a computation of the sampling error.

53 Estimation methods based on sampling techniques

531 Area estimation from maps. Within an exactly known total area (overall area of the map, for instance), the principle of these methods is to determine the proportion of the total area occupied by a given forest class. The estimate of this proportion is given through a systematic layout of either:

- dots, to each of which is attached the value 1 if it is inside the forest class or 0 if it is outside (dot grid system);

- or parallel lines (or "transects") to each of which is attached the part of its length within the forest class; the transect system is less used than the dot grid system since the lengths have to be measured.

The areas of the forest class have to be estimated by multiplying the number of dots within the class (dot grid system), or the sum of the lengths of the parts of transects within the class, by an area extension factor (area of the unit square of the dot grid or unit length multiplied by distance between two neighbouring transects).

The error formula given in paragraph 422 of Chapter 3 for estimation of a proportion is not applicable in the case of the dot grid method as the dots (sampling units) are systematically distributed. Several authors have worked on the problem of error estimation in dot grid measurements, and error formulas have been developed. An acceptable approximation of the standard error is given by the following formula (after Chevrou - 1971):

$$e(\%) = 56.5 \frac{\sqrt{k}}{n^{3/4}}$$

where:

$e(\%)$ is the error in percentage on the estimated area of a forest class;
n is the number of dots found within this forest class;
k is a factor depending on the shape of this area, and increases as the area becomes more irregular; for more regular shapes the value of this coefficient is said to be between 5 to 7.

Taking a conservative value for k equal to 7 we will have approximately

$e(\%) = \frac{150}{n^{3/4}}$ corresponding to the following values for n:

e%	10	5	2	1	0.5
n	37	93	310	780	1970

Each dot count must be carefully performed and repeated, preferably by another operator. If the two counts differ significantly, at least one other count must be carried out. Use of small hand counters is recommended in order to avoid mistakes in enumeration. Counting can be restricted to marginal parts of the area, the central part being divided into rectangles or squares of known area. If a slight discrepancy is found between the sum of the areas of the forest classes estimated by dot count and the exact known value of this total, each individual area has to be corrected by the ratio of this exact value to the estimated total.

Estimation by dot counts and by planimetering can be combined in certain cases. For instance the areas of the inventory units can be estimated by planimetering, the estimates being corrected by the ratio of the exact value of the total inventoried area to the sum of the estimated areas of the inventory units, and the areas of the strata within the inventory units can be calculated from dot counts and corrected according to the same principle.

532 Area estimation from photographs

Sampling designs in which the dots are replaced by "photoplots" are generally used. The delineation of the forest classes on the photographs is not necessary unless the number of plots per photograph is large. Examples of one- or two-stage sampling designs have already been described in paragraph 334.2. Other designs are possible: for instance one can imagine a three-stage sampling design wherein the primary units are parallel, but non-adjacent strips, the secondary units are photographs within these strips and the tertiary units are the photo-plots on the effective area of each selected photograph. Multi-stage sampling designs can also be foreseen using different photographic coverage, for instance one space satellite coverage plus two aerial coverages, one of the latter at small-scale and the other at a larger scale (see paragraph 622).

54 Continuous area estimation

By "continuous area estimation" is meant the estimation of areas at different times using successive photographic coverages. Repeated estimations of forest areas are of utmost importance in the tropics as the forest cover is endangered in many places and it is necessary to monitor these changes in order to achieve better control and to develop appropriate land-use policy. The statistical basis for such studies is regression analysis and some methods used are identical to those used for continuous forest inventory in the field (see Chapter 7). The different coverages can be either complete or partial. If the first one is complete, the estimation of change can be assessed through a new partial coverage using simple regression estimation (such a study was performed in the Ivory Coast using a complete coverage of 1956 at a scale of 1/50,000 and a partial coverage of 1966 at a scale of 1/40,000).

If only one old complete or partial coverage is available, and if no significant interpretation error is foreseen, the estimation of change can be obtained by regression analysis from a ground check of photo plots precisely located in the field and interpreted previously on the photographs.

A part of the photoplots previously interpreted on the old coverage can be interpreted again on the subsequent coverage, as in continuous forest inventory, after carefully transferring them from the old photographs onto the new ones, and or each further coverage a partial sample of new photoplots can be interpreted.

It is thought that with the rapid development of remote sensing techniques and the increasing concern for the maintenance of the forest cover these studies on forest monitoring will develop considerably in the near future at the local and national levels as well as at the regional and world levels. Sampling theory offers a lot of very useful and efficient techniques provided they are utilized carefully and on a sound basis.

6 Recent developments in remote sensing and mapping techniques

61 Brief presentation of recent techniques

611 New forms of remote sensing. The principle of conventional panchromatic aerial photographs can be stated as follows:

By means of a film covered with a silver salt emulsion they reproduce the relative intensities of the natural electromagnetic radiations of all the bands of the visible spectrum (the bands may be limited by a filter), the camera being situated aboard an aircraft. Innovations in remote sensing with respect to normal panchromatic aerial photography relate simultaneously to one or more of the characteristics mentioned in this definition.

611.1 New platforms

a) The orbiting of manned or unmanned artificial satellites has now become a commonplace operation. When such satellites are fitted with remote sensors (cameras or scanners) and with devices for storing or transmitting the images or signals collected (television system, reproduction of signals on magnetic tape), one can obtain actual or televised photographic images, or data recorded on magnetic tape or disc, corresponding to the radiations received from the overflown areas. The images obtained have the following advantages:

- they can cover a very large area in a single exposure (approximately 3 million ha for 70 x 70 mm negatives at a scale of 1/2,500,000);
- distortions due to relief are negligible and the picture has the planimetric value of a map.

The images suffer from one major drawback, namely their poor ground resolution 1/ which corresponds to a dimension generally exceeding 80 m. Ground resolution is limited primarily by the height of the spacecraft, but it also depends on the nature of the image obtained. If the photograph is taken directly on a sensitive film, ground resolution will also depend on the fineness of the emulsion grain. When the picture is televised, i.e. from an unmanned satellite, ground resolution will depend on the scanning intensity of the television system.

b) Experiments have been conducted in Canada with very large-scale photographs (1/1,500 and over) taken from helicopters or light aircraft. Such coverage is designed to identify certain species (e.g. Picea glauca and Abies balsamea), to quantify the damage caused by epidemics and insect attacks and to assess the characteristics of forest potential by means of photogrammetric measurements and "aerial" volume tables. Experiments on species identification from very large-scale aerial photographs have also been performed in tropical American forests.

1/ i.e. the size of the smallest object detectable on the image for a specified contrast.

The most difficult problem has been to develop a precise height-finding system, an accurate measurement of the camera's height from the ground being essential for a proper estimate of scale and, consequently, sufficiently precise photogrammetric data; the first altimeters used worked on radar which did not penetrate all plant cover.

611.2 <u>Other electromagnetic radiation</u>

The following table taken from the book "Remote Sensing, with special reference to Agriculture and Forestry" (U.S. National Academy of Science) indicates the wavelength and frequency intervals of the different electromagnetic radiations as well as the corresponding sensors used to study natural resources.

Panchromatic photographs employ the reflection by objects of electromagnetic radiations of the visible spectrum with a wavelength ranging from 0.38 μ to 0.78 μ. The real innovation in the field of remote sensing, admittedly less spectacular than the use of space platforms, has been the use of radiation intervals other than those of the visible spectrum.

The use of part of the <u>near infra-red</u> (from 0.78 μ to 0.90 μ) in association with visible radiations of 0.5 μ (or 0.6 μ) to 0.78 μ has already been dealt with in paragraph 321.22.

Spectral region		Wavelength	Currently used imaging sensors
Microwave (radar)	Decimetre Centimetre Millimetre	10-100 cm 1-10 cm 0.1-1 cm	Scanning antennas
Infra-red radiation	Far IR Intermediate IR	8-1,000 μ 3-8 μ	Scanners with IR detectors
	Near IR	0.780-3 μ	Photographic film to approximately 1 μ Scanners with IR detectors
Ultra-violet radiation	Near UV Middle UV	0.315-0.380 μ 0.280-0.315 μ	Photographic film (quartz lens). Scanners with photo-electric sensors.

The use of <u>"thermal" infra-red</u> (3-14 μ) - the radiations emitted in greater quantity by hotter bodies - is especially suitable for the detection of latent fires and of diseases and insect attacks affecting the forest (these result in a slight heating of the vegetation).

<u>Radar radiation</u> (between 0.5 cm and 1 m and especially between 0.86 cm and 3.3 cm) possesses the great advantage of being able to penetrate cloud formations and of being relatively little attenuated by rain. Its use is proving very interesting in tropical regions where conventional photographic coverage is a time-consuming procedure because of the nearly permanent presence of a rather low cloud base.

611.3 Scanners

The use of new radiations and requirements for continuous automatic re-transmission (especially from unmanned satellites) have led to the increased use of scanners. A simple scanner consists of an optical device (generally a rotating mirror coupled to a parabolic mirror) and a sensor which converts into electric signals the variations in the intensity of radiation in a certain band of the spectrum (like a photo-electric cell). Through the movement of its optical system and of the aircraft, the scanner examines the scene to be observed in parallel contiguous strips. The electric signals are then received in a cathode ray tube for display on a television screen or for printing on a sensitive film. They can also be transcribed onto magnetic tape and then processed by computer.

611.4 Artificial radiation

The radiations used in conventional photography are natural radiations reflected by the object photographed and which come mainly from the sun, either directly or indirectly via other objects that have relayed these radiations by reflection or transmission. Certain remote sensing systems (active radar devices) employ specially emitted (artificial) radiations which are reflected back by the objects photographed. Such systems can also perform sensing at night without difficulty.

611.5 Band selection

Another important element in the field of remote sensing is the separate reception of the radiation received on each waveband. The advantage of isolating certain spectrum bands is obvious. For example, two objects to be differentiated may reflect with the same overall intensity the total radiation of the visible spectrum whilst reflecting with very different intensities a specified band of the visible spectrum. In other words, their "signature", or response with respect to that band, will be different and distinction between them will be clearer.

Application of the principle of band selection is not new in fact; the yellow filter intended to stop radiation with a wavelength of under 0.50 μ is an example of selection in that it amounts to selecting the 0.50 μ to 0.78 μ band of the visible spectrum. Conventional colour photography also involves such selection, as in these emulsions a yellow layer receives 0.38 μ to 0.48 μ radiation, a magenta layer 0.50 μ to 0.58 μ radiation, a cyan layer 0.60 μ to 0.78 μ, the three images being superimposed (unlike black-and-white panchromatic film on which a single image is formed). An interesting example of colour film is the spectrozonal film used in the U.S.S.R.; its emulsion possesses only two layers and it has proved very useful in forestry.

Separate recording of the images in the different bands is effected essentially in two new ways:

- by combinations of several cameras (up to 27 in one case) or by cameras with several lenses where each camera (or each lens) corresponds to a specific emulsion/filter combination; thus different simultaneous images of the same scene are produced, each corresponding to a particular band of the spectrum;

- by an equivalent system in which the camera, or cameras, are replaced by sensors; for example, the "multispectral line scanner" system, in which several scanners operate together, each one reproducing the radiation emitted by the object in a specific band of the spectrum; it has a single optical device beaming the total radiation onto a prism which scatters it according to wavelength; the scattered radiation passes through a number of sensors, each of which is sensitive to a given band of the spectrum, and the resulting signals are then converted either into a televised image or into a photographic image (in both cases through a cathode ray tube), or yet again into data stored on a magnetic base.

612 New media for information storage and reproduction. The information collected has so far been assembled in the form of black-and-white or colour photographs on an opaque or transparent base, in negative or positive form, produced directly by simple chemical reaction development on the sensitized film. For a long time to come the forester will continue to use this type of information base for much of his work.

The major innovation in the field of reproduction is the use of the cathode ray tube. The electrical data transmitted by a sensor are converted by the tube into visible information. It is the principle of television applied to the recording of radiations which are not limited to the visible spectrum. The picture obtained may therefore be a black-and-white or colour image on a television screen, or it may be obtained directly by sensitizing a film at the output of the tube. In this way black-and-white cliches are obtained from radiation in the thermal infra-red or radar radiation. These same cliches can be converted into pictures in standard coded colours where each shade of grey is represented by a colour and a shade in that colour, thus permitting naked-eye differentiations which would be impossible on the corresponding black-and-white cliché. Electric impulses at the scanner output can also be stored on magnetic tapes or discs.

613 New procedures for information analysis. Analysis of conventional aerial photographs - photo-interpretation - employs the human eye and brain aided by optical devices (magnifying equipment, stereoscopes). Despite the great weaknesses of human interpretation, this type of analysis will continue to be done both on conventional pictures and on black-and-white and colour pictures corresponding to radiations outside the visible spectrum.

A simple device which can improve the human interpretation of the cliches obtained is additive viewing. This consists of the projection onto a single screen, through particular colour filters and with varying intensities, of positive black-and-white transparencies - each corresponding to a given waveband. The result obtained is a "false colour" picture. The value of this device lies in the fact that the different shades of grey are converted into a much greater number of colours and colour shades (chromas, hues, and values). By altering the filters one can obtain the false colour image that best displays the difference between two objects that would otherwise be undetectable on black-and-white cliches.

Microdensitometric analysis is a technique whereby a light spot scans a photographic transparency and the variations in luminous intensity transmitted through the photograph are transcribed onto a graph. The system operates by means of a sensor which converts the variations in luminous intensity into electric impulses, the impulses being amplified and transmitted through a scribing arm to the graph. A type of crown can thus be reproduced as a certain curve shape. One can imagine the possibilities of this method. For example, if the type of curve corresponding to a given species is fed into a computer together with the tolerated fluctuations, it becomes possible, with the microdensitometric device linked to the computer, to count (and perform calculations on) the number of corresponding crowns encountered.

More generally, the introduction into a computer of the magnetic media storing all the data relating to the electric signals produced by scanners sensing the radiation from the observed scene (or from a photographic image of it) permits automatic (and objective) processing of the data. If it is likewise given the data on the aircraft's path the computer can thus make it possible for instance to locate the hot points observed by the thermal infra-red sensor. The advantages in many cases of such automatic processing over human interpretation are clear, especially for radiation outside the visible spectrum where the cliches obtained have a poor resemblance to the visual images to which we are accustomed.

614 Orthophotography. A new technique has been developed for plotting from aerial photographs. It consists of reproducing photographically and without geographical distortion the portion of land common to the two photographs of a stereogram. Orthophotography is therefore photographic plotting as opposed to the conventional cartographic plotting which results in topographic maps. All the orthophotographs for a particular region can therefore be brought together to form what is called an orthophotoplan which has the same planimetric value as a map. The lines traced on the stereograms - such as boundaries of forest types and, of course, contour lines - can be automatically reproduced on the orthophotoplan. Plotting of forest boundaries can also be done under a stereoscope from the stereogram composed of the worked up photograph and the corresponding orthophotograph.

The chief interest of this device is that it allows more thorough and concrete mapping than normal mapping. It is also about ten times quicker. Its price remains high; for example, plotting by orthophotography of the useful part of a 23 x 23 cm negative costs between US$ 80 and 140, the price depending on the scale and on the quantity of additional information to be plotted (e.g. boundaries of forest types). If contour plotting is added to this, the cost ranges between about US $ 160 and 250.

62 Current operational applications for forest inventory

The possible combinations of these different innovations are, of course, extremely numerous and an immense field of application lies open in the field of natural resources evaluation. Applications in forestry and in vegetation studies are at the present time largely in the research and experiment phase. In general, their use, even when no spatial observations are involved, assumes a technological infrastructure and financial resources which are not available to all institutes or even to all governments. The following paragraphs simply indicate the accessible and/or operational procedures in the field of forest resources evaluation.

621 Use of radiation outside the visible spectrum

621.1 Use of radiation in the thermal infra-red

Systems for the early detection of forest fires are worth mentioning although they are not directly relevant to forest inventory. One employs an aircraft flying at a height of 7,000 m deploying a scanner recording IR radiations of 3 to 6 μ and 8 to 14 μ. Electric signals corresponding to radiations of 8 to 14 μ are transmitted to a cathode ray tube and continuously act on a film which is developed very rapidly. The 3 to 6 μ radiation band is used to indicate hot points at the moment when they are sensed. A computer which integrates the data on the aircraft's path (ground speed, altitude, bearing, drift) determines the film speed and makes a mark on the border of the film corresponding to unit distances covered. If a hot spot is overflown its coordinate along the line of flight is also indicated on the border of the film, thus making it easy to pinpoint and analyse it. Action can then be taken before the fire develops.

621.2 Use of radar radiation

An "active" radar device (i.e. one recording the beam reflected by ground objects of the radiations emitted by itself) has been successfully used in one of the dense tropical forest zones of Latin America (Nicaragua, southeast Panama and northwest Colombia) and has permitted mapping of zones permanently covered by a fairly low cloud base. Another very important "active" radar mapping operation was carried out in the northwestern part of Brasilian Amazonia.

The basic principle is still the same; namely, a scanner (in this case an antenna) covering the observed terrain in strips transverse to the direction of flight, electric signals being introduced into a cathode ray tube which continuously sensitises a film.

One feature of these devices which should be noted is that the photographed strip is not situated vertically underneath the aircraft but to one side (side-looking radar); this allows better determination of the distance to the ground from chronometric measurements.

The original scale of the pictures obtained in Panama was around 1/200,000. In the southeast region (southern part of the province of Darien) they have allowed satisfactory planimetric mapping at a scale of 1/250,000 and mapping of vegetation by major classes. The control pointsused were small metal pyramids cleared of all vegetation, possessing known coordinates and easily located on the radar pictures.

622 Use of space platforms

622.1 Earth Resource Technology Satellite (ERTS) Programme

Several thousands of satellites have already been launched for various purposes (weather observation, intercontinental broadcasts, radiation studies, etc.). In the field of natural resources evaluation, data obtained from flights such as Gemini and Apollo have opened the way to special studies. A great step forward was taken in July 1972 with the launching in the United States of the first Earth Resources Technology Satellite (ERTS-A).

The characteristics of this flight were the following:

- lifetime: 1 year;
- altitude: 920 km on a sun-synchronous orbit;
- repeated coverage of the same zone every 18 days;
- earth distance between two passes: 160 km;
- satellite-borne sensors:
  - a television system (RBV) recording images in three bands of the visible spectrum and of the near infra-red;
  - a multiple scanner (MSS) recording images in four bands of the visible spectrum and infra-red; the electric signals are coded and recorded on tape.

The scale of the original pictures obtained (70 mm) - for each band and also for the composite colour pictures - is about 1/2,500,000. Each negative corresponds to a 180 km square, i.e. 33,000 km^2. Ground resolution of the negatives varies between 60 and 150 m depending on the contrast of the scene examined and the sensor concerned. Longitudinal and lateral overlap is low, around 15%. At the time this manual is written it is too early to indicate what is the real value of this imagery for forest inventory in the tropics, but it can be predicted that it may be very useful for broad vegetation and forest typing in large-scale forest surveys, especially if combined with other photographic coverages as indicated in the following paragraph.

622.2 Multi-stage designs using space photographs

A statistical design, simple in its principle though more complex in its mathematical formulation, has been conceived for inventories of vast areas 1/. It uses spatial photographic coverage on which a square grid is superimposed. A number of squares are selected proportionally to the forest area they contain, the latter being determined by interpretation of the space photographs. Small-scale (1/30,000 to 1/70,000) aerial photographic coverage is then carried out on these selected squares. This

1/ See "The benefits of multi-stage variable probability sampling using space and aircraft imagery" by Philip G. Langley in "Application of remote sensors in forestry", joint report by working group on Remote Sensing of former Section 25 of IUFRO.

coverage is, in turn, divided into a grid from which squares are selected on the same basis as previously, and these squares are photographed on a larger scale (1/5,000 to 1/25,000). Finally, field sampling plots are selected within the latter squares, and the results of the field work are applied to the whole zone. This method will probably prove profitable when spatial coverage is readily available, but it is limited by its nature to national or regional inventory operations.

CHAPTER V

MEASUREMENT CONSIDERATIONS

CHAPTER V

MEASUREMENT CONSIDERATIONS

1 Introduction

In addition to the areas, there are many characteristics of the forest stands which it is useful to know for their management and that inventory is aimed at estimating. The most common and generally the most important characteristics are related to the volume of wood: gross or net or extractable volumes, by species, groups of species, by diameter classes or groups of diameter classes, by quantity classes, down to a minimum diameter, estimated at the time of the inventory or subsequently (through the estimation of volume increment), etc. But often other characteristics are just as, if not more, important. Numbers of stems by area unit, by species and diameter classes are basic parameters which are generally easy to determine from the basic inventory data and are necessary in forest management. Other parameters related to the volume of wood may be more interesting to know than the volume itself: for instance in many forest inventories it would be more important to estimate the wood potential in terms of value, taking into consideration the different species and types of the standing volume. Assessment of quantities of other forest products, such as cork, is sometimes the main objective of a forest inventory. In almost all forest inventories additional parameters have to be estimated, such as those related to site and accessibility. The contents of this chapter will be restricted to the problems of volume estimation, quality appraisal and accessibility assessment.

In most forest inventories volume information is obtained from the field inventory, although stratification by photointerpretation may be based on items in relation with the total volume of the stands (such as density and height of the dominant trees). However, in some temperate countries, when species identification is feasible on aerial photographs, most of the volume information is taken from the photographs through photogrammetric measurements, the remaining part of this information being obtained from a few field samples. This method which has proved efficient for some temperate forests is not applicable to the mixed tropical forests. For this reason photogrammetric measurements for volume estimation will not be considered in this chapter.

Volume estimation is based on measurements of tree or stand characteristics (diameter, height, basal area ...) and on quantity relationships between those measured characteristics and the volumes to be estimated, whereas the assessment of quality of wood and to a lesser extent the evaluation of accessibility is based, at least partly, on personal judgement and is consequently less objective. Although this cannot be avoided, the extent of subjectivity should be restricted to a minimum in order to avoid discrepancies in estimation between different taxators and even for the same taxator throughout the inventory. For instance, quotations of quality (allocation of a given tree or parts of a tree to a given quality class) must correspond to the occurrence of one or a given number of precisely defined defects. The quality class has to be narrow enough to make the exercise worthwhile but at the same time wide enough to make it less difficult and in the end more reliable. The problem is similar for the assessment of some accessibility and logging parameters such as soil-bearing capacity or irregularities of terrain which are not measured, strictly speaking, but are only qualified by reference to a given class.

A broad classification of inventory measurements not directly related to area determination is the following:

a) tree and log measurements on standing or felled trees

- enumeration and species identification: the assignment of a tree to the sample is preliminary to further measurement and is sometimes done through a measuring instrument (such as the Bitterlich relascope in horizontal point sampling).

Species identification, although not strictly speaking a measurement, is a fundamental operation and sometimes difficult and time-consuming (especially in inventories of mixed tropical hardwoods);

- measurements of diameter (over bark or under bark) at breast height, at the stump, at various levels on the upper stem, of diameter increment, height and length (total, of the bole, of the merchantable bole, from the ground or from the top of the buttresses, up to a given diameter), of bark thickness and of characteristics related to minor products (such as cork thickness);

b) <u>other measurements</u>

- regeneration counts by species and by density classes of seedlings, by height and/or diameter classes of saplings and poles;

- measurements for site quality assessment: in addition to the measurement of some tree and stand characteristics, site quality can be assessed by counts of ground and scrub vegetation and measurements of parameters related to soils and to topography;

- measurement of accessibility parameters;

- various measurements such as seed collection parameters for individual species.

c) <u>quality appraisal and other evaluation without true measurements</u>, mainly for stand description, site quality and accessibility.

2 <u>Tree measurements</u>

21 Definition of te:

The following definitions have served for forest inventories carried out by FAO.

a) <u>Stem</u>: for trees of deliquescent form, the length of the trunk between ground level and the crown point (see below for the definition of the crown point); for trees of excurrent form the length of the trunk between ground level and the top of the tree.

<u>Remark</u>: Deliquescent formed trees, especially broadleaved species, have a stem which is strongly evident in the lower portion but, due to branching, becomes less distinguishable in the upper crown (many trees of tropical broadleaved species have however a clear bole up to the crown point and the stem is easily distinguishable). Excurrent-formed trees examplified by numerous coniferous species have a definite central stem which extends from ground to top. When there is a fork, the number of stems to be recorded depends on the location of the fork with regard to the reference height for diameter measurement (breast height for non-buttressed trees): if at the reference height the main stem is already divided in two or more stems, these latter have to be recorded instead of the main stem.

b) <u>Crown point</u>: the crown point is located at the origin of the lowest crown-forming branches, living or dead; at this point in many broadleaved species the stem starts to disperse into the crown; isolated single branches below this point, if they are at a distance of more than half a specified log length from other branches, should not be used to determine the crown point.

c) <u>D.b.h.</u>: the diameter at 1.30 metres (4.3 feet) above ground level (for trees standing on slopes, the point of measurement must be determined on the uphill side).

Case of buttressed trees: if buttresses exist and are higher than the breast height level, d.b.h. measurements are useless: buttresses are often irregular in cross section, are difficult to measure at standard breast height with accuracy and their dimensions have a loose relationship with the volume of the tree; a satisfactory standard procedure for measuring the diameter of buttressed trees has still not been developed and different procedures have been used up to now: measurement just above the termination of swelling or irregularity or at a given distance above that point (30 centimetres was recommended for FAO inventory operations in the former edition of this manual).

Remarks: Clear definitions or instructions have to be given to inventory crews as to how and where to measure the d.b.h. (definition of "ground level", of d.b.h. for buttressed trees, of d.b.h. for stems of irregular form, etc...). This is a fundamental prerequisite in obtaining basic data as homogeneous as possible. The definitions used should be as identical as possible to those commonly used elsewhere. Comparability of inventory results is sometimes impossible due to differences in the definitions between inventories. 4 feet 3 inches should be taken as equivalent to 1.30 m and not 4 feet 6 inches as in North America. For the sake of comparability and consistence (see paragraph 24) diameter measurements and diameter classes should be used rather than girth measurements.

d) Height and length measurements: The following classification of height and length measurements on standing trees (adapted from "Forest Mensuration" by Husch, Miller and Beers) and illustrated in figure V-1 has served for inventories carried out by FAO.

- Total height: the vertical distance between ground level and top of the tree.

- Bole height: the distance between ground level and crown point: it expresses the height of the clean, main stem of a tree.

- Merchantable height: the distance between ground level and the terminal position of the last usable portion of a tree.

  There are several criteria which can define this upper terminal and the exact location is, to a large extent, subjective and made more problematical due to the difficulty of sighting the upper part of a stem in a tree crown under forest conditions. The upper position may be defined by a chosen minimum top diameter or by branching, irregular form, defect, etc., which limits what is considered the utilisable wood in a stem. The merchantable height may be up to a minimum top diameter or below but never above it. The minimum top diameter chosen will depend on the intended use of the wood in the stem. The definition of the utilisable wood and of the corresponding eliminating defects must be as precise as possible in order to reduce the personal component to a minimum (and preferably to zero).

- Stump height: the distance between ground level and the basal position of the main stem where a tree is cut.

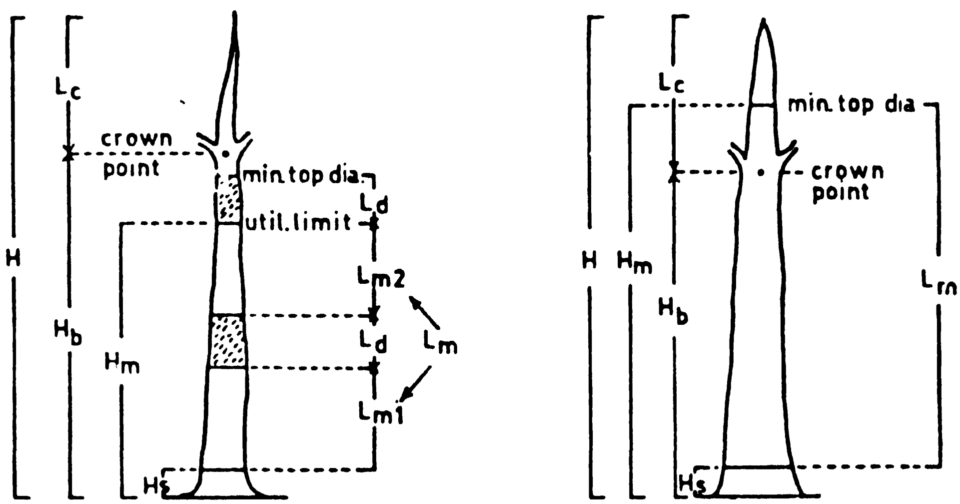
  This length depends on cutting practices. For the buttressed trees in the tropics, stump height is generally considered just above the buttresses.

- Merchantable length: the sum of the lengths of the portions of a tree which are cut and utilised: this includes material such as trim allowance which may be wasted in the manufacturing process.

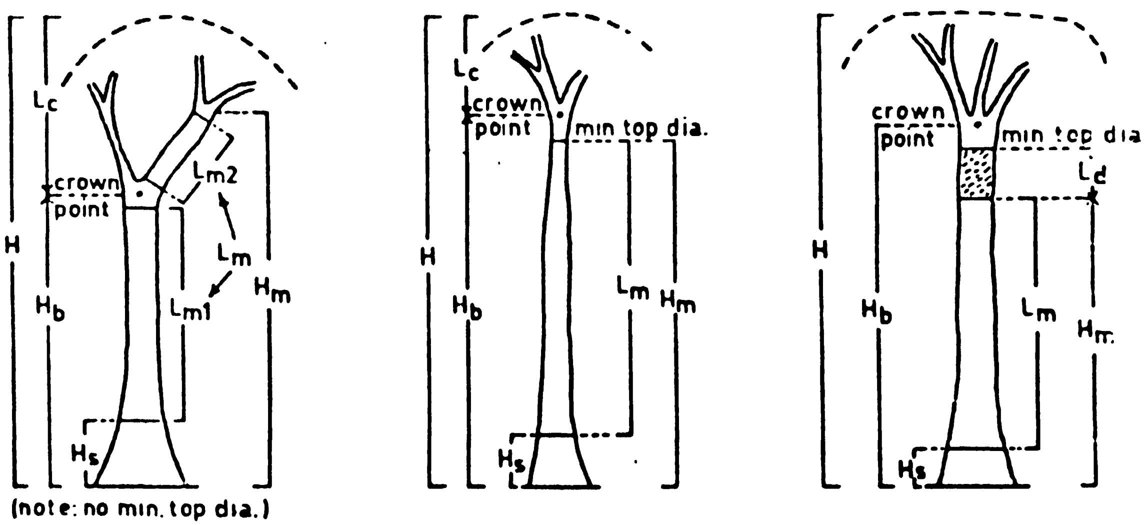
  There are three major difficulties in the assessment of merchantable length on standing trees. The evaluation of the external defects on the upper parts of the stem by an observer at ground level may not be precise enough unless

Figure V- 1 Tree height and stem length classification

a. Excurrent form



b. Deliquescent form



binoculars are used. Secondly the logs deemed merchantable by the inventory people may not be identical to those cut by the logger. This is particularly true for mixed tropical hardwoods due to the changing conditions in local and international markets, in accessibility of the inventoried zone and in logging practices. Finally the assessment of merchantable length on standing trees takes only the external defects into account in most cases and not inner defects which are often more decisive factors of merchantibility.

- Defective length: the sum of the lengths of the portion of the stem which diameter is larger than the minimum acceptable but which cannot be utilised because of some kind of defect.

  The same remarks as fo the assessment of merchantable lengths on standing trees apply in the case of defective lengths.

- Crown length: the distance between crown point and the tip of the tree.

  Height measurements of standing trees are vertical distances while length measurements may be made on sections whose axis departs from the vertical. Additionally, a merchantable height may include some defective lengths below the point defining the upper limit of merchantability. Consequently it is possible that the totals of length measurements may not agree with height measurements, e.g. the total of merchantable lengths may not agree with the merchantable height for a tree.

22 Enumeration

Before any tree is measured, it must be decided whether the tree belongs to the ample or not. This is the principle of enumeration and its importance must not be underestimated. Enumeration is not the same in sampling units of a given area and in point or line sampling.

221 Enumeration in sampling with units of a given area. Enumeration consists of two checks:

a) whether the tree is within the sampling unit: the distance of the axis of the tree from the centre of the plot (circular plots) or from a side (or an axis) of the plot (square or rectangular plots) must be smaller than a given length; precise instructions have to be given to the inventory crews as to how to measure this distance, and whether the distance is to be measured horizontally or along the terrain, as well as particular indications on borderline trees;

b) whether the characteristics of the tree make it enumerable: these characteristics are its species (see paragraph 23 for problems of species identification), since in some inventories, especially in the tropics, several species are not recorded, or its dimensions; generally the dimensional criterion for enumerable trees is a minimum diameter and more measurements must be made than the ones which are recorded (see paragraph 24 for measurement problems).

222 Enumeration in point or line sampling. The selection of the trees to be recorded is made by means of a measuring instrument. In horizontal point sampling which is the most common sampling design of that type, a tree is selected if its horizontal distance R from the sampling point is smaller than its diameter D divided by a certain factor k equal in the metric system to

$$\frac{1}{50}\sqrt{(BAF)},\ (BAF)$$

being called the basal area factor of the instrument: $R < \frac{D}{k} = \frac{D}{\frac{1}{50}\sqrt{(BAF)}} = \frac{D}{2\sin\frac{\phi}{2}}$

Θ is the horizontal gauge angle of the instrument (angle of sight from the sampling point of a borderline tree); and

$BAF = 10{,}000 \sin^2 \frac{\Theta}{2}$ (in the metric system)

Every tree in the surroundings of the point which satisfies the species and minimum size requirements and with $R < \frac{D}{k}$ belongs to the sample.

Once the tree is known to belong to the sample, then other measurements on this tree may be made. Sometimes point sampling is used only for estimating the basal area of the stand: in each sampling point the basal area per hectare G is equal to:

$G = p \times BAF$

where p is the number of trees around the sampling point for which $R < \frac{D}{k}$.

R and Θ are measured in the horizontal plan of the observer's eye. In inclined terrain a correction has to be introduced for every tree in relation to the slope of the sight line of the tree. Simple angle gauges and prisms do not permit automatic correction whereas the Bitterlich relascopes make provision for it.

23 Species identification

Species identification poses some problems in inventories of tropical mixed forests. The relatively large number of tree species, the restriction of botanical knowledge to a few individuals, the similar appearance of trees of different species, make species identification particularly difficult. Nevertheless good identification of the species is a fundamental prerequisite of any forest inventory: it is much more serious in most cases to make a mistake concerning the species of a tree than to make it about one or several of its dimensions.

In many tropical forest inventories it is hardly feasible to combine perfect botanical work and satisfactory efficiency. Indeed it is generally too time-consuming to assure a completely accurate species identification. The following indications have to be kept in mind when looking for a compromise between the conflicting requirements of botanical exactitude and of efficiency.

a) It is often not necessary to identify all the trees botanically within the whole inventory sample. In view of this, several devices can be adopted such as:

- enumeration of a limited number of commercial and commercializable species ("desirable" species) in the entire inventory sample and enumeration of all species in a subsample in order to reduce the costs of the inventory and at the same time to obtain an acceptable knowledge of the floristic composition of the inventoried forests;

- enumeration of all trees with a diameter larger than the minimum exploitable diameter and of the trees of the "desirable" species below this diameter: this device saves quite a lot of time as a large number of small trees do not have to be measured and recorded;

- species with very little occurrence which have very little chance of being used need not be identified with certainty and can be merged under one or several groups of "undetermined", possibly by botanical families.

The selection of one or the other of the two first devices assumes that the "desirable" species can be perfectly identified.

b) In order to record less trees, and taking into account the fact that the coefficients of variation of parameters related to smaller diameter classes are often lower than those for large diameter classes, it is useful to adopt different sizes of sampling units (or of the sample) according to diameter classes: for instance each sampling unit or recording unit may consist of two or three concentric circular plots, the smaller circle being the sampling unit or the recording unit of the smaller diameter classes.

c) Once the different characteristics of the enumeration work has been decided, efforts should be aimed at securing species identification by every possible means, among which can be quoted the following:

- thorough and intensive training of the treespotters, preferably in different parts of the inventoried zone;

- limited number and permanence of the treespotters in order to obtain the most homogeneous data;

- establishment of a corresponding list of local (vernacular) names and scientific names: this is generally a long and difficult task since the criteria of classification used by the botanists on the one hand and the bush people on the other are different, resulting in many discrepancies, e.g. several local names for the same species depending on the age and sex of the tree, or, on the other hand, one local name only for several species and sometimes genera, the traditional use of which is at the same time identical and limited;

- assessment of simple and practical field identification keys based on a limited number of characteristics such as bark, slash of bark, leaves and fruit;

- preliminary collection of wood, leaf and fruit samples for reference purposes throughout the inventory;

- control checks by a botanist or the best treespotter in randomly selected sampling units, immediate analysis of the results and consequent further instructions to the crews;

- use of systematic botanical check procedures such as the following which was used in Sarawak: a sample of leaves was collected and put in a separate bag for every tree of the sample, the bags being further despatched to a botanist who crosschecked the local name given by the treespotter and his own identification.

If rectifications in the enumeration work related to species identification are to be made in the course of the inventory, attention must be paid to the way they are introduced. In order to get homogeneous data in all inventory units, it is better to avoid introducing these corrections in the inventory units wherein the enumeration work has already started, unless enumeration is entirely taken up in these units.

24 Measurements

Estimation of the volumes of the trees of the field sample and of the stands is made through measurements of characteristics of these trees: diameter - at breast height and at any other level of the stem or possibly of the branches (on felled trees); height up to a given level of the stem, or length along the stem or the branches, and bark thickness - generally at breast height only on standing trees. Measurements are made either on standing trees or on felled trees, especially for the assessment of volume relationships.

241 <u>Measurement units</u>. <u>The use of the metric system is highly recommended</u> as it is the most practical and as most countries have adopted it or intend to adopt it in the near future. Conversion to volume and weight units through appropriate relationships is also easier with the metric system. Diameter is generally expressed in centimetres, or sometimes in metres. Height and length are practically always expressed in metres and bark thickness is often given in millimetres. Diameter increment is determined in centimetres or millimetres.

In countries where the British System is presently used, it is advisable to convert the linear results directly obtained from the measurements into metric units as for the volume results.

242 <u>Measurement classes</u>

242.1 It could be imagined that all measurements are taken to the smallest possible discernible unit or part of unit. This would be unrealistic, mainly because measurement errors in a forest inventory are often greater than the nearest unit. As this might also be more expensive, many measurements - with the exception of bark and diameter increment measurements - are made by classes.

The amplitude of the classes used for diameter, height and length measurement is determined in the light of such factors as:

- instruments and devices used for measuring and their accuracy;
- environmental conditions such as visibility and tree form;
- skill and training of the crews;
- homogeneity and comparability of data from different inventories.

Regarding the last consideration the following remarks can be made:

a) the amplitude of the diameter classes used in the metric system is generally 5 or 10 cm, the minimum diameters being a multiple of 2.5 cm. However, due to the different minimum diameters adopted (5 cm, 7.5 cm, 10 cm, 15 cm) it is not always feasible to make easy comparisons between inventories;

b) when using British measurements, one should try to use class limits approximately equal to class limits in the metric system, which means diameter classes equal to 2 or 4 inches, and length or height classes equal to 5 or 10 feet; the attached table shows the minimum standard class limits which are recommended for FAO inventories in the metric and British systems;

c) when the inventory users are interested only in volume estimates, the use of classes of equal basal area amplitude (basal area classes) instead of diameter classes may be recommended; the volume estimates obtained through volume relationships are indeed statistically more valid when they are derived from enumeration with basal area classes than when derived from enumeration with diameter classes; basal area classes can be used for instance in an inventory of tropical mixed hardwoods for trees above the minimum exploitability diameter (volume estimates above this diameter) whereas diameter classes are used for trees below this diameter, since estimates of numbers by diameter classes of these stems are more useful for management purposes than volume estimates. Moreover, such a system can be applied insofar as comparability of inventories is possible, i.e. when one is interested only in the comparison of volume estimates above the minimum exploitability diameter.

Standard Minimum Diameter and Height Class Limits for Inventory Calculations and Results

Diameter

Metric System cm.	Approx. equivalent in British system ins.	Actual equivalents in cm.
0 - 5	0 - 2	0.00 - 5.08
5 - 10	2 - 4	5.08 - 10.16
10 - 15	4 - 6	10.16 - 15.24
15 - 20	6 - 8	15.24 - 20.32
20 - 25	8 - 10	20.32 - 25.40
25 - 30	10 - 12	25.40 - 30.48
etc.	etc.	etc.

Height

	Metric System cm.		Approx. equivalent in British system ins.		Actual equivalents in cm.
0- 3	0.0 - 0.3	0 - 10	0 - 1	0.0 - 3.048	0.0 - 0.305
	0.3 - 1.5		1 - 5		0.305 - 1.524
	1.5 - 3.0		5 - 10		1.524 - 3.048
	3 - 6		10 - 20		3.048 - 6.096
	6 - 9		20 - 30		6.096 - 9.144
	9 - 12		30 - 40		9.144 - 12.192
	12 - 15		40 - 50		12.192 - 15.240
	15 - 18		50 - 60		15.240 - 18.288
	18 - 21		60 - 70		18.288 - 21.336
	21 - 24		70 - 80		21.336 - 24.384
	24 - 27		80 - 90		24.384 - 27.432
	27 - 30		90 - 100		27.432 - 30.480
	30 - 40		100 - 130		30.48 - 39.62
	40 - 50		130 - 160		39.62 - 48.77
	50 - 60		160 - 190		48.77 - 57.91
	etc.				

242.2 Understandably the precision of the inventory results is affected by the class grouping of the basic measurement data and that the larger the classes the more significant the corresponding errors. A thorough analysis of this type of error is made in "Forest Inventory", vol. II by Loetsch, Zöhrer and Haller (pages 85 to 90), which can be presented concisely as follows:

- there are two components of this error;
- a systematic component (bias) originates from the difference between the actual mean diameter of the trees within a diameter class and the midclass diameter, and/or from the difference between the mean basal area of the trees of this diameter class and the basal area corresponding to the midclass diameter; these differences come from the distribution of the diameters within the diameter class;
- a random component comes from the fact that, in a forest inventory, only a sample of trees of a given diameter class is measured and the estimate of the mean diameter of this class (and of the mean basal area) has a sampling error (in general the estimate of the mean diameter of the class from the sample is not equal to the actual mean diameter of this class, itself different from the mid-class diameter in many cases - see above).

It is complicated to have to take this type of error into account in the error calculation of the final results. The best solution is to adopt small classes since the magnitude of these errors increases with the amplitude of the classes, and to consider that the corresponding errors are negligible.

243 Measurement procedures and instruments. It is not intended to describe and comment on the various instruments used for measuring diameter, height, length and bark thickness, but rather to give some information and advice on measurement procedures which are more directly relevant to inventories in mixed tropical hardwoods. More complete information is available in forest mensuration and forest inventory publications as well as in advertising leaflets published by the manufacturers.

243.1 Diameter measurements

243.11 Diameter at breast height

For reasons mainly of practicability calipers are little used in tropical forest inventories: the fairly large size of the trees, the occurrence of high buttresses, of aerial roots, the difficult working conditions make the use of calipers little adapted to these forests.

Girth tapes are used on felled trees and on standing trees with buttresses less than approximately 2 metres high. Regarding the use of tapes in tropical forest inventories, the following indications are worth mentioning:

- fibreglass tapes often prove to be the most suitable;
- a hook at the zero of the tape permits the measurement of large trees by one person;
- risk of tilt from the horizontal plan of measurement and of looseness of the tape is relatively high with large trees and great care must be exercised in having the tape well stretched in the horizontal plan of measurement;

creepers along the bole are very common and they must be cut at the height of the measurement or the tape must be put below them if this is feasible;

- graduations of diameters in length units (centimetres or inches) or diameter class limits must be indicated on one face of the tape; purchase of tapes with a blank face where limits of the adopted diameter classes are further marked with special ink is recommended.

For trees with "diameter at breast height" higher than 2 metres, procedures and instruments for measurement of upper stem diameters have to be used.

243.12 Upper stem diameters

Many fairly sophisticated instruments of varying degrees of accuracy have been devised for the measurement of diameters at various heights of the bole. The simplest ones are not necessarily the least accurate and much depends on the way they are handled and consequently on the training of the inventory staff.

When the reference height is relatively small (measurements of diameters above buttresses) a simple graduated rule at the top of a metallic or wooden pole held close to the bole and facing the observer, with the zero in coincidence with one side of the bole, can be considered a suitable instrument in the case of measurement by diameter classes. As the observer in a tropical forest cannot stand very far from the tree (generally not more than 15 metres), parallax error is not negligible: graduations of the rule have to be corrected to take the parallax error for a given horizontal distance between the observer and the tree into account. This simple device has been used in many forest inventories in West Africa. The Finnish parabolic caliper and other simple instruments based on the principle of the Biltmore stick can also be used for measurement of diameters above buttresses or at relatively small heights.

Instruments for measuring diameters at any height are more sophisticated and more expensive. In order of increasing sophistication the more interesting ones are:

- the Wheeler pentaprism which consists of a metallic rail with one fixed and one sliding prism, the distance between the two prisms being equal to the measured diameter; the only drawback of this simple and precise instrument is that the rail must be as long as the maximum diameter to be measured, which does not permit its use for the biggest trees in tropical inventories;

- instruments such as the "Diatromb" wherein two indices are put in optical coincidence with the edges of the stem and are at a fixed horizontal distance from the eye of the observer (the indices are fitted on a bar sliding on a rod, the distance between the eye at the end of the rod and this bar being such that its horizontal projection is constant);

- the multi-purpose Bitterlich relascope which permits simultaneous measurement of the height and of the diameter of the stem at this height; the wide-scale relascope has proved to be useful for measurement of upper stem diameter in tropical forests, although visibility in these forests is not always sufficient to permit accurate measurements;

- the Barr and Stroud dendrometer has magnifying optics, uses split-image coincidence and is a very precise but rather expensive instrument.

243.2 Height measurements

Height measurements in a forest inventory are made:

a) on all trees (or a fraction of them) of the sample in connection with measurements of upper stem diameters when the volume of the standing trees of the sample is estimated by geometric formulas using these measurement data;

b) on all trees (or a fraction of them) of the sample in addition to the d.b.h. when the volume of the trees of the sample is estimated through volume equations using diameter and height as independent parameters;

c) on a relatively small subsample of trees in connection with measurements of upper stem diameters, the volume of these trees being estimated by geometric formulas, and the volume, d.b.h., and height data being utilized for the sessment of volume equations by regression analysis.

Height measurements, like measurements of upper stem diameters, are indirect measurements made by optical instruments (contrary to d.b.h. which is generally a direct and rapid measurement) and are consequently time-consuming. When selecting the method of volume estimation in a forest inventory, it should be carefully checked whether these additional measurements on all the trees of the sample (or on a significant part of them) are justified. In many inventories of mixed tropical hardwoods it has been found that it is more efficient to use "local volume tables" (1) by species with measurement of d.b.h. only on all the trees of the sample than to use volume equations with d.b.h. and height as independent parameters with measurement of d.b.h. and height on all the trees of the sample: the increase in precision is small in relation to the consequent increase in the enumeration cost (see below paragraph 342.2).

As for the measurement of upper stem diameters, many instruments exist and the less expensive and sophisticated ones may be particularly useful in certain conditions and especially in some tropical forest inventories. Direct measurement with telescopic poles is possible only for small heights - for greater heights (total height, bole height, merchantable height of usual trees) indirect measurement by hypsometers has to be used. The Christen hypsometer is a very cheap and handy instrument which is recommended for tropical forest inventories when the precision required is not very high. Other well-known hypsometers such as the Blume-Leiss or Haga hypsometers are more precise but measurements are more time-consuming and sometimes require too great a distance between the observer and the tree in tropical forests with a thick undergrowth. Clinometers, such as the Suunto clinometer, can be used also but the heights cannot be read directly and have to be calculated from the slopes measured with the instrument. The Bitterlich relascope is used also for height measurements generally in connection with upper stem diameter measurements.

243.3 Bark measurements

All diameters, at breast height and on the upper stem, are measurements over bark on the standing trees, but merchantable volumes do not include the volume of the bark. The problem is to relate the volumes under bark of the tree with the diameters over bark and possibly also with measurements of the bark.

If the volume of the standing trees of the sample is estimated without the help of volume equations, volumes under bark have to be estimated from volumes over bark using a conversion factor calculated from bark measurement at breast height.

If volume equations are used and established from a sample of felled trees, the best solution is to estimate the volumes under bark of these sample trees and to relate these volumes through regression analysis to the d.b.h. over bark (and possible height and other upper stem diameters over bark). In this case bark thickness is measured with a rule on the face of the logs.

The most common bark gauges for measuring bark thickness at breast height on standing trees have been designed in Sweden. Risks of underestimation and overestimation in bark thickness measurements are numerous and much care and training is necessary.

(1) Volume equations wherein volume is a function of d.b.h. only.

3 Volume estimation

31 Definition of volumes

It is of the utmost importance to define the volumes referred to in an inventory clearly and objectively. There are unfortunately too many inventory documents wherein it is not clearly stated which is the minimum d.b.h. of the corresponding trees, which portions of the trees are considered (are branches included ? what is the minimum top diameter ?), whether or not the volume of bark is included, whether the volumes are gross volumes or exclude defective parts, which the criteria are for excluding parts as defective, whether the "net" or "utilizable" volumes correspond to what is likely to be extracted or do not exclude the logging losses, etc. It is easily understandable that the definition by an adjective such as "gross", "net" or "industrial" is generally not sufficient, and must be completed by a clear explanation of the adjective itself.

The drawbacks of a lack of definition or of an incomplete or unprecise definition are serious. For instance when the inventory results are used for a feasibility study, misinterpretation of the concept of volume jeopardizes the whole study. In particular, this happens when the incompletely defined inventory volumes are considered as extractable volumes although they are "gross" or "net" volumes including logging losses.

The following definitions were included in the first edition of this Manual as standard definitions for all FAO forest inventories:

Gross volume: the volume of a specified portion of a tree without bark(1) or deduction for defects; when used, the term should be qualified by a word or statement specifying the portion of the tree to which it refers, e.g. total tree gross volume (2).

Net volume: the volume of a specified portion of a tree without bark and with deductions made for defects or unusable material; the term should also be qualified according to the portion of the tree to which it refers.

Total volume: the volume included in the main stem of a tree; for deliquescent-formed trees, up to the crown point; for excurrent-formed trees up to the tip of the tree.

Branch volume: for excurrent-formed trees, the volume of all branches; for deliquescent-formed trees, the volume above the crown point (and any branches which may occur below).

Industrial volume: the potentially usable net volume of round wood, without deduction for losses due to utilization standards of logging and manufacturing processes; it equals the sum of log volumes plus other usable volume.

Log volume: the net volume of a tree considered suitable for veneer logs, sawlogs, sleeper logs, piling and poles; this volume may also be used for pulpwood, chipboard or other industrial use.

Other usable volume: the net volume of a tree not suitable for purposes listed under log volume but usable for posts, pulpwood, chipboard and for other industrial use.

(1) Gross volumes include bark volume in many inventories.

(2) Gross volumes as well as all other volumes refer to a minimum d.b.h. of the relevant trees and also to a minimum diameter at the small end of the stem and branches.

In addition to the above definitions the following remarks can be made.

a) It is suggested that the adjective "commercial" when added to the terms "industrial", "log" or "other usable volume" or to specified portions of the volumes, distinguishes volume which can be economically removed under given conditions.

b) To estimate commercial or merchantable volumes it is necessary to know the merchantability specifications for a given species or group of species at the time of the inventory (i.e. for known and specific wood products and situation of the wood market), for a given situation of logging and for the inventoried area or for a neighbouring and similar area. To assess the merchantable volumes it is generally necessary to complete the inventory operation itself by measurements in the logging units of the extracted logs, and of the losses in order to determine the ratio of the extracted merchantable volumes to the inventory volumes. This is particularly true in inventories of mixed tropical forests for which no tradition of exploitation exists and changes in market and infrastructure are rapid and significant. "Commercial" volumes are inventory results which can be given only when such "utilisation studies" (or "recovery studies" or "harvesting-intensity studies") are thoroughly carried out. If this is not the case the adjective "commercial" is inappropriate and must not be used.

c) In no case should the expression "net volumes" be used or understood as synonymous with "commercial volumes". The only quality assessment (or grading) of the standing trees of the sample cannot provide a satisfactory estimate of the merchantable volumes as these latter are determined also by the internal defects, the logging damage (splits, broken trees, etc....) and other factors which cannot be precisely predicted from observation of the trees of the sample. Drilling of trees at breast height for rot determination (see paragraph 42 below) is useful for the assessment of decay occurrence which provides additional information on the quality of the standing trees, but still other parameters must be ascertained for a valid assessment of commercial volumes.

d) The actual usefulness of the assessment of "net volumes" thus does not appear fundamental, as these are generally different from the commercial volumes which are in most inventories among the most important results to obtain. This is all the more true as some subjectivity and personal bias is almost unavoidable in the assessment of net volumes. In many tropical forest inventories procedures such as the following can be adopted:

1. use the inventory measurements themselves excluding basic quality data, to determine gross standing volumes objectively;

2. use the basic quality data to classify (or "stratify") these gross standing volumes by quality classes (or grades), the basic quality data being obtained by observation of external defects, by decay information at breast height on standing trees and possibly also by detailed quality analysis of a subsample of felled trees;

3. perform a recovery study by making a survey of the output in a sample of logging units, a partial recovery factor being determined for each of the former grades or quality classes of the standing volumes.

32 Volume units

Volume estimates can be expressed either in cubic units showing the total contents of a tree (or portion specified), or in terms of the quantity of the ultimate products which can be processed from the tree or section. The North American board foot unit is such an end product volume. The use of an estimated end product volume has the advantage of a direct assessment of final products expected, and thus facilitates evaluation. However,

this type of measurement unit has significant shortcomings in that it shows the estimated output in terms of only one product, sawn boards or lumber, and for sawlogs this volume depends on the amount of defects in the log, the skill of the sawyer, the thickness of the saws used, the thickness of the lumber sawn and the amount of taper in the log. There is indeed a general implicit agreement in tropical forest inventories to limit the volume estimation at the exit of the logging unit or sometimes to the yard of the wood mills. In view of the above and other limitations it seems logical to follow this latter custom and to abandon the use of end product volume units. Additional results in board foot units will be given only when it is considered essential.

As for linear measurements (see above paragraph 241) the use of the metric system (cubic metres as volume units) is highly recommended. In countries where the British system is still in use, it may be advisable to produce results in cubic feet and also in cubic metres: many of these countries intend to shift to the metric system in the future, and international statistics on wood resources could be facilitated. The use of the metric system and of both systems in countries using the British system has been recommended as a standard procedure in all forest inventories carried out by FAO.

33 Classification of volume estimation techniques

The values of the known parameters measured and recorded in the sample are used to estimate the means and totals of these parameters or of other related characteristics in the inventoried forest area and in parts of it. Mean and total volumes are among the main estimates to obtain from the inventory.

All observations made in the sampling units for volume estimation are observations on trees. In the first step of the volume estimation process these observations are used either for assessing the volumes of the trees in the sampling units (and consequently the corresponding volumes of the stand in the sampling units) or for directly estimating the stand characteristics in the sampling units. A simple example of this latter case is the sweep with a Bitterlich relascope made at a point in a plantation, the sampling unit being the point and the stand characteristic being its basal area at this point; the elementary observations are made on the trees around this point, but the individual tree volumes are not (and cannot) be estimated from this simple observation.

The estimation of the individual tree volumes in the first case or the direct estimation of the stand volumes in each sampling unit in the second case can be made

- either by formulas (such as geometric formulas for volumes of simple solids) and graphic procedures, provided that sufficient detailed measurements are made;
- or by quantitative relationships between the few(1) measured parameters and the volumes, such as volume equations established by regression analysis.

In view of the above two considerations a general classification of volume estimation techniques could be the following:

1. volume estimation techniques on a tree basis
   11. without "quantitative relationships"
   12. with "quantitative relationships"

2. volume estimation techniques on a stand basis
   21. without "quantitative relationships"
   22. with "quantitative relationships"

the expression "quantitative relationships" being synonymous with relations derived from

(1) In most cases for estimation of individual tree volumes the measured parameters are limited to diameter at breast height and height (total, or merchantable, etc.).

other trees or stands[1] and of restricted application: the volume equations, for instance, are generally valid for a given region, for a given site quality, for a given species or group of species, sometimes for a given range of d.b.h., etc. (The principles of this classification are taken from "Planning a forest inventory" by B. Husch, but the classification is presented in a different order.)

The following development will be restricted to the problems of volume estimation on a tree basis as this type of volume estimation is more frequently used in forest inventory, especially in the tropics where most of the stands are mixed and uneven.

34 Volume estimation on a tree basis

341 Geometric formulas applied to standing or felled trees. The total volume of a stem (or its volume up to a minimum diameter) is expressed by the well-known formula:

$$V = f.g.h$$

where f, g and h stand respectively for the form factor, the basal area at breast height (or above buttresses) and the total height of the stem (from the stump or from the buttresses) or up to minimum diameter.

If it is generally possible to determine the basal area at breast height and the height effectively and with reasonable accuracy, this is not the case for the form factor, since the form of the stem is not easy to characterize and may not be uniform all along the stem. In addition the volumes to be estimated may include the volume of the branches, and in this case the ratio of the volume to the product basal area x height is even more difficult to estimate.

The most obvious way of computing the volume(s) of a single tree is to divide it (virtually with an optical device if it is standing) in sections of equal or unequal length (logs or "frustums" of the stem, branches in certain cases), to estimate by geometric formulas the volume of these individual parts and then to add the volumes so obtained. The geometric formulas giving the volume of a section from its length and diameters at the ends and/or at mid-length cannot give completely accurate results as a log is never identical to one of the simplest corresponding geometric solids. But their accuracy is generally sufficient with respect to the measurement errors and it is all the more true as the number of sections is higher.

The usual geometric formulas are:

- Smalian's formula: $v = \frac{g_b + g_u}{2} L$

- Huber's formula: $v = g_m L$

- Newton's formula: $v = \frac{g_b + 4g_m + g_u}{6} L$

where:

v is the volume of the log

g_b is the cross-sectional area at base : $g_b = \frac{\pi}{4} d_b^2$

g_m is the cross-sectional area at middle: $g_m = \frac{\pi}{4} d_m^2$

g_u is the cross-sectional area at top: $g_u = \frac{\pi}{4} d_u^2$

L is the length of the log

(1) However these trees or stands must belong in principle to the inventoried population.

(The volumes considered can be volumes over bark or volumes under bark with, in this latter case, the diameters d_b, d_m, d_u being measured under bark.)

These three formulas are valid if the log can be assimilated to a frustum of paraboloid of revolution. Newton's formula is also applicable if the log is approximately a frustum of cone or of neloid; for these two latter cases, Huber's formula gives an underestimation of the volume of the log whereas Smalian's formula gives an over-estimation which is twice as big as the underestimation of Huber's formula.

The use of Newton's formula is highly recommended when the logs are long, i.e. when the number of logs per tree is small, and of course when the whole stem is not divided into sections. This means that to estimate the volume of a stem up to a given minimum top diameter there must be at least two diameter measurements - at stump height or above the buttresses, and at mid-point between stump and the minimum top diameter - and the measurement of the height from the stump to the minimum top diameter.

There are three usual ways of dividing a stem:

- division in sections of equal length from the stump, the last section often being assimilated to a simple fraction of this unit length; this procedure is the most common in forest inventory;

- division in sections such as the difference between their diameters at large and small ends is constant: the lengths of the sections are generally different unless the tree form is conic;

- division in sections of unequal length using the measurements at breast height: in a European national forest inventory the following diameters are measured on all trees of the sample: stump diameter, diameter at breast height (1.30 m), diameter at 2.60 m, diameter at merchantable height (or minimum diameter) and diameter at mid-point between 2.60 m and the merchantable height; then the tree volume is computed by applying Newton's formula to each of the two logs, the lower log with a length of approximately 2.6 metres and the upper one from 2.60 metres to the minimum top diameter.

The instruments used for measuring upper-stem diameter and height for estimation of volumes of standing trees were presented briefly in paragraph 243. The Bitterlich relascopes used with a tripod prove to be very useful dendrometers for the simultaneous measurement of diameters and lengths of the various sections. Volumes of standing sample trees for the assessment of volume equations in tropical forest inventories have often been computed from relascope measurements on standing trees, when felling of trees for this purpose was not possible.

342 Volume equations

342.1 Introduction

The expression "volume equations" is used rather than the more common one "volume tables" in order to indicate that only equations (or formulas) giving the volume of a tree ("dependent variate") as a function of the characteristics (mainly diameter at breast height and height) and derived from statistical regression analysis, are dealt with in this paragraph.

The expression "volume tables" includes indeed not only the volume tables drawn from this type of equation, but also those which were (and sometimes still are) established by graphical or "semi-graphical" methods (like Keen and Page's method) which should no longer be used, as they include some personal bias and do not allow for a sound estimation of the statistical error.

The advantage of the use of volume equations in forest inventory is evident; they permit, from detailed measurements on a limited number of trees judiciously selected within the forested area ("sample trees"), the objective estimation of the volume of a much larger number of trees in the sampling units and finally the estimation of the total and mean volumes within the inventoried area.

The construction of volume equations is a difficult, time-consuming and expensive task. Once it has been decided in a forest inventory to estimate the volume of the trees of the sample by use of volume equations (and not by additional measurements on the trees) there is a tendency to reduce the work related to the assessment of volume equations without valid reasons. For instance, it may happen that volume equations are already available and that the need for their adjustment or for new ones is not felt. It is very important, however, to check carefully whether the equations are valid, in general, and applicable in the particular case of the inventory to be carried out. In paragraph 342.4 some indications will be given on the statistical validity of volume equations. As for their application to a given inventory many questions have to be answered positively: is the form of the trees in the inventoried zone similar to that of the trees of another region used for the volume equations (in the case of volume equations with diameter and height as independent variates) ? Is the average height per diameter class of a given species the in the two regions (in the case of "local" volume tables for one species with only d.b.h. as independent variate) ? Is the species composition in the inventoried zone similar to that of the region of the sample trees used for the volume tables, when the volume equation is used for the trees whatever the species ? If the available "local" volume tables are for groups of species, is the representation of each species in the group identical in the inventoried zone and in the area for which the volume tables were initially constructed ? etc...

To check the applicability of the available volume equations objectively, a field test is strongly recommended. This may be done by directly determining the volume of a number of judiciously selected trees from the forested area to be inventoried using the same measurement standards and methods as employed for these volume equations. The volumes of these trees are also read from the volume equations being tested. The percentage of divergence of the individual actual volumes from those of the equations is then computed. These percentages may be tabulated and averaged for the same species or group of species by diameter (and possibly also height) classes. If they reveal a significant difference in volume, the equations may be considered not applicable or requiring adjustment before use.

An inappropriate set of volume equations or, more generally, bad volume equations, whether constructed for this inventory or not, may significantly reduce the reliability of the results. This is all the more true as the sampling error due to the inventory sampling itself is low: in this case a large component of the total error (including the measurement errors) may unexpectedly be due to the use of the volume equations.

The methods used for volume estimation by volume equation are statistical methods. Some of them - method of least squares, principally, but also some "non-parametric" multivariate analysis methods and automatic classification - consist purely in mathematical computations and are used for the assessment of the equations. Regression analysis on the contrary serves for the application of the equation to the trees in the sampling units and cannot be applied without restrictive conditions. In other words it is always possible to establish by a mathematical method a relation of a statistical nature between the volume and some characteristics of sample trees, but if we want to know the statistical error corresponding to the application of this equation to a tree or group of trees in the population, some conditions must be fulfilled which we shall deal with in paragraph 342.4.

342.2 Basic types of volume equations

The most significant measured characteristic to which the volume(s) of a tree is (are) related is its d.b.h. Therefore all volume equations will have d.b.h. and possibly exponents and functions of d.b.h. as independent variates. Very often one height - either total height or bole height or any other specified height - and exponents or functions of this height are added to d.b.h. Finally other characteristics are introduced in the most elaborated ones, such as bark thickness or some form quotients (i.e. ratios between two diameters at different heights of the stem).

Thus volume equations can be grouped into the tree following categories:

a) "local" volume tables which relate the volume(s) of a tree only to d.b.h. or exponents and functions of d.b.h. (such as basal area). The two most common ones are:

$$v = a_o + a_1 d^2$$

$$\log v = b_o + b_1 \log d \quad \text{or } v = B_o d^{b_1}$$

(with $B_o = 10^{b_o}$ or e^{b_o} whether the logarithms are decimal or naperian)

with: d = diameter at breast height (d.b.h.)

a_o, a_1, b_o, b_1 = constants

b) "standard" volume equations which include as independent variates d.b.h. and a given height, and functions of these two characteristics. The most common "standard" volume equation is:

$$v = c_o + c_1 d^2 h$$

with d = diameter at breast height (d.b.h.)

h = total height, or bole height, or any merchantable or other height

c_o and c_1 = constants

c) more elaborated volume equations specially developed for research purposes or for national forest surveys and which include d.b.h., one or several heights and other characteristics.

Which of these types of volume equations to choose for a given forest inventory is a difficult question. In many tropical forest inventories the choice is often between "local" volume equations for every species or group of species and possibly by part of the inventoried area and "standard" volume equations for all species or for groups of species. There is no general solution, and each case must be studied carefully taking into consideration the total precision required, the costs involved in both solutions and logistic problems. However, regarding this problem, two remarks are worth mentioning:

a) It has been found in some mixed tropical hardwoods (e.g. semi-deciduous and evergreen forests in west Africa) that, for a given species or possibly group of species, the average bole height (from top of buttress to crown point) in every diameter class above a certain diameter (say 50 centimetres) was nearly constant. Since the most important volumes are generally those of trees above this diameter (which is, in many countries, the minimum diameter of exploitability) the inclusion of bole height in the volume equation does not appear essential, provided that the number of trees in the sampling

units of the corresponding species in each diameter class is large enough and that the variability within each diameter class around this constant mean is relatively small.

b) The use of a "standard" table implies the measurement of a height on every tree within the sampling units, or at least on a part of them. The additional cost is significant since the time required for enumeration may be double or even longer. On the other hand the reduction of the sampling error due to the use of a "standard" table instead of a "local" table may be insignificant in relation to the total error which includes the sampling error of the sampling design and the measurement errors. In such cases the use of local volume tables proves to be more efficient since the increase of the sampling error is more than compensated by the reduction of the cost.

342.3 Combined types of volume equations

In some recent inventories, the volume equation approach is not as simple as those described above and consists in a more or less complicated combination of "standard" and "local" volume equations. The main purpose of this type of procedure is to avoid the measurement of the second characteristic (height) on every tree of the inventory sample while trying at the same time to reduce the sampling error due to the use of volume equations. Many procedures of this type can be contemplated, and it is impossible to list and describe them all. The following two examples give a good illustration of this type of approach.

1st example. Volume equation of the FAO/UNDP nationwide forest inventory in West Malaysia.

a) Description of the measurements made:

- d.b.h. over bark (D_s) and height class on all the 41,200 trees of the inventory sample;
- d.b.h. (D_s), diameter at 16 feet (D_{16}), diameter at 32 feet (D_{32}), diameter at crown point (D_c) (all diameters over bark) and bole height (H) on 16,600 trees out of 41,200 of the inventory sample (subsample) for determination by geometric formulas of an estimate V_s of the volume of the standing tree;
- detailed measurements for accurate determination of the volume of the bole (V_F) on 720 felled trees out of 16,600.

b) Procedure followed:

- assessment of one equation (by method of least squares) between V_F and V_s, V_s being calculated from the measurements D_s, D_{16}, D_{32}, D_c and H made on the standing trees, from the 720 felled trees:

$$V_F = a + b\,V_s + c\,V_s^2 ;$$

- application of this latter equation to the 16,600 trees for determination of their (estimated) V_F;
- assessment of local volume equations (by method of least squares) by species and height class from the 16,600 trees of the type:

$$V_F = a_i' + b_i'\,D_s + c_i'\,D_s^2 \quad (i = 1 \text{ to total number of species x height classes});$$

- application of these local volume equations to the 41,200 trees of the inventory sample for the estimation of the volumes in each sampling unit.

2nd example. Volume equations of the FAO/UNDP inventory in the Aures Mountains in Algeria (by the Spanish consulting firm O.T.I.).

a) Description of the measurements made:

- in the sampling units of each compartment: measurement of diameter at breast height over bark, D_s, on all trees and measurement of total height H on a subsample of trees;
- detailed measurements for accurate determination of the volume (V) of a small subsample of trees (336 Pinus halepensis trees and 5? Cedrus trees).

b) Procedure followed:

- assessment of one "standard" volume equation (by the method of least squares) for each of the two species, from the small subsample of trees:

$$V = a + bH + cD_s^2 + dD_s^2 H \quad \text{for Pinus halepensis}$$

$$V = a' + b' D_s^2 H \quad \text{for Cedrus}$$

- application of these "standard" volume equations to the subsample of trees of each compartment for the estimation of their volume V_s;
- assessment of five equations (by method of least squares) between H and D_s, each equation corresponding to one stratum (site quality):

$$H = a_i'' + b_i'' D_s + c_i'' D_s^2 \quad (i = 1 \text{ to } 5)$$

- allocation of each compartment to one of the five strata with the use of the height measurements in the subsample of the compartment;
- assessment of one "local" volume equation per species and per stratum between V_s and D_s from the subsample of trees of each species and of all compartments of the stratum considered:

$$V_s = a_j''' + b_j''' D_s + c_j''' D_s^2 \quad (j = 1 \text{ to total number of species x stratum classes})$$

- application of these "local" volume equations to all the trees of the inventory sample for the estimation of the volumes in the sampling units.

The type of approach illustrated by the above two samples can be considered generally as more efficient than a simple conventional approach using only one type of volume equations. However, their relative efficiency cannot be assessed precisely as the complex procedure makes the computation of the sampling error too difficult if not impossible. It is of the utmost importance, as for the simple approach, to ascertain fulfilment of the conditions required for the use of statistical methods at each step of the procedure.

342.4 Statistical aspects of the volume equation approach

In many forest inventories using the volume equation approach for the estimation of the volume(s) of the trees, insufficient consideration is given to the statistical aspects, and more precisely to the statistical requirements, which must be fulfilled to get reliable estimates of the volumes and of the sampling errors of these estimates. Up to now there is no evidence in forest literature that all these aspects have been treated, and there is an urgent need for a clarification of all the related problems. The following considerations are no more than general indications and recommendations.

Selection of the sample trees

Geographic distribution of the plots from which the sample trees are selected should preferably be based on an objective sampling design either at random or systematic, or on a stratified random or stratified systematic design (by forest type, for instance). Concentration of sample felled trees in a very limited number of locations within the forest area is often decided upon for evident logistic and economic reasons. However, it must be realized, even if the location of these large plots is determined objectively - which should always be the case - that the more concentrated the sample, the larger is likely to be the sampling error. Again for logistic and economic reasons the sample trees are often selected close to roads or to openings; in such cases, a bias in volume estimation may occur as the growing conditions of the trees are different.

Regarding the distribution per species and/or per diameter class the problem is more complicated. A representative distribution of the sample trees (i.e. proportional to the tree occurrence) among the species and/or the diameter class appears intuitively the surest method, if not the best. However, some considerations may preclude the use of a representative sample; for instance, such a sample often results in a large uncertainty in the volume estimates of the biggest trees since these are little represented in the population. It may be more efficient to solve this problem by proportioning the number of sample trees per diameter class to the relative volumes of each class in the whole population (which is in many cases close to a Neyman's allocation). In each location, the sample trees can be selected by relascope in such a way as to approach more closely this optimum allocation. The rejection of trees from the sample because such characteristics as crooks, leaning trees, forked trees, etc. must be done on a sound basis. A general principle is that no sample tree should be rejected if the corresponding volume equation is applicable to any tree of the same standards within the forested area. The only exception to this rule should be when the tree cannot be accurately measured (for instance when creepers and foliaceous epiphytic vegetation make diameter measurements unreliable).

There is no universal answer as to the number of sample trees to be selected for any one volume equation. The larger the number the more precise will be the estimate, but it also depends on many other factors such as the diameter and the height range of the trees, the size of the area, the number of forest types, the variation of site factors, etc. "Local" volume equations in limited areas for a given species or group of species have been constructed with 100, or even less, sample trees.

Problems of regression analysis

a) Once the sample trees have been selected and measured, and their volumes computed, the scatter diagram with the volumes, V, on the y-axis and the main independent variates, d.b.h., or $(d.b.h.)^2 x\ H$, on the x-axis is drawn. A first visual observation will give an idea of the strength and form of the correlation, and will show any need for more sample trees in certain classes of the independent variate and the possible abnormalities which may result from measurement or computation errors.

The observation of the scatter diagram will also show if it has to be split in two or more parts corresponding to different portions of the range of values of the dependent variates. If this is the case there will be a need for two or more volume equations.

b) If the variation of the volume within a class of the independent variate increases with this variate, it will be necessary:

- either to transform the dependent and independent variates (for instance by the use of a logarithmic transformation) in order to get a more satisfactory scatter diagram;
- or to weight all the variates in each class of the dependent variates by a quantity proportional to the inverse of the standard deviation of the volumes in this class;
- or to use both procedures together.

The constance of the variance of the dependent variate within each class of the independent variates is a prerequisite of regression analysis. If this condition is not fulfilled, the strength of the relationship between the volume and the independent variates cannot be evaluated and the sampling error cannot be determined. Generally, the variance of the volume in each class of the independent variates can be said to be proportional to $(dbh)^2$ (or to a larger exponent of dbh) or to $(dbh)^2 \times H$ (or to a larger exponent of this product). The regression between V and dbh for instance ("local" volume equation) of the model: $V = a + b(dbh)^2$, with a variance proportional to $(dbh)^4$ is transformed in the following regression:

$$\frac{V}{(dbh)^2}$$

(wherein the variates have been weighted by $\frac{1}{(dbh)^2}$ which is proportional to the inverse of the standard deviation of the volume).

c) Then a <u>model</u> of volume equation has to be chosen. The choice of the most suitable model is facilitated by observation of the scatter diagram of the <u>weighted and/or transformed variates</u> : if the curve

$$\left[\frac{V}{(dbh)^2} , \frac{1}{(dbh)^2} \right]$$

of the above example shows a parabolic tendency toward the x-axis, it may be convenient to adopt the following amended model:

$$\frac{V}{(dbh)^2} \qquad \frac{}{(dbh)^2} + b + \frac{}{(dbh)}$$

which will result finally in the following volume equation:

$$V = a + c(dbh) + b(dbh)^2$$

Another way of constructing the model is to draw up a list of the most significant weighted (or transformed) expressions of the independent variates, for instance:

$\frac{1}{(dbh)^2}$, $\frac{1}{dbh}$, constant, $\frac{H}{dbh}$, H, $\frac{H}{(dbh)^2}$ (expressions, respectively weighted by $\frac{1}{(dbh)^2}$, of: constant, dbh, $(dbh)^2$, $(dbh)H$, $(dbh)^2H$, H)

and to apply the so-called <u>multiple stepwise regression</u> analysis. Computer programmes for this method exist which provide a set of volume equations, the first one including only one expression of the independent variate

(for instance $\frac{V}{(dbh)^2} = \frac{a}{(dbh)^2} + b$)

and each of the subsequent ones differing from the former by the inclusion of an additional variate. The last one is the most complete and precise, but the gain in precision from the preceding one may not be significant. Interpretation of the computer outputs and selection of the inputs in these programmes require the assistance of a statistician. Some <u>constraints</u> can be added to the model in these programmes, such as a fixed value of the constant in the equations.

With the development of automatic data processing, the use of weighting (including the research of the best weight) and of stepwise regression analysis should be practised to an increasing extent. These techniques allow for a sound estimation of the statistical errors in the use of volume equations.

Statistical errors in the use of volume equations

The validity of the adjustment by regression analysis can be tested by the value of the multiple correlation coefficient, which is equal to the correlation coefficient when the dependent variate (volume) is a function of only one expression of the independent variates, for instance: $V = a + b(dbh)^2$. This adjustment will become more valid as this coefficient approaches 1 (maximum value of the coefficient in the case of a perfect adjustment).

Estimation of the variance and standard error of the mean value of the volume given by the equation for given values of the independent variates, and estimation of the standard error of the application of this value to the trees of the inventory sample with the same characteristics, are given by rather sophisticated formulas, and advice from a statistician would have to be sought for detailed information. The problem posed by the combination of the error with the error due to the inventory sampling is a difficult question which does not seem to have been very much dealt with in the forestry literature. Here too, the advice of a specialist must be sought as it is necessary to know what is the incidence of the volume equations on the total error of the volume estimates.

Grouping of the species

In certain cases, and especially in inventories of mixed tropical hardwoods, it is not possible to assess separate volume equations for each different species. Various solutions are possible:

- assess separate volume equations for the most important species and apply a common volume equation for the remaining ones;
- assess separate volume equations for the most important species and group each of the remaining species with one of these species, by a comparative study either of the form factor (in the case of "standard" volume tables) or of the diameter-height diagram (in the case of "local" volume tables);
- group the species by homogeneous classes in order to get more sample trees for each volume equation.

This last grouping can be done more or less objectively by comparison of scatter diagrams corresponding to different species, by a covariance analysis by groups of two species (when the number of species is small), or by a statistical method of automatic classification (multivariate analysis plus cluster analysis). The two latter methods are the best and the most comprehensive and objective ones, but they require a sufficient expertise and the availability of appropriate computer programmes. Here too, the assistance of a statistician is necessary.

343 Volume estimation by taper functions. Taper functions are assessed by regression analysis and generally give, for a species or a group of species in a given area, the ratio of the diameter of the stem at a given height to the diameter at breast height (or above the buttresses), expressed as a function of this given height. Within the same species or group of species there may be different taper functions according to the diameter classes.

Once the taper functions are determined, the volume of a tree in a sampling unit, whose d.b.h. and bole height (or other height) has been measured can be easily calculated by dividing the whole stem into frustums of equal length and adding their volumes. The volumes of the individual frustums are calculated by geometric formulas using the diameters given by the taper function. The rather lengthy computation of the volume of each tree of the sample is not a problem when an electronic computer is available.

The remarks made in paragraph 342.4 on the statistical aspects of volume equations are equally valid here since regression analysis is used in both cases. In particular, the problem of the grouping of species (and/or of diameter classes within the same species) can be solved in the same way. The solution adopted should be the most objective possible, taking into account costs and other limiting factors.

344 Selection of the most suitable volume estimation technique. There is no general answer as to the best volume estimation technique to be used in a forest inventory. Volume estimations by additional measurements on the trees of the sample or by use of regression analysis (volume equations, taper functions) both have advantages and shortcomings which are summarized below.

The main advantage of volume estimation from additional measurements on standing trees is that there is no sampling error on the estimation of the volume, the only sampling error being that arising from the sampling design of the inventory. There are some drawbacks; the main one is the additional cost due to a longer enumeration work, another one being the additional measurement errors which may be important and difficult to assess precisely.

Methods based on volume equations and taper functions introduce an additional component to the sampling error which may be significant with respect to the other components (other sampling and measurement errors). There may also be some bias at one or several of the steps of the construction of volume equations or of taper functions. The advantages are important: in comparison with the direct method of volume estimation it generally costs considerably less; the volume equations can be used for further inventories and other purposes and will remain as a tool for the forester which can be refined later on; the measurement data collected for the construction of volume equations, which are generally more detailed than in the other method, may serve as a basic material for further mensuration studies. These advantages are of particular interest in many developing countries of the tropical world where forest mensuration is a new research field and where mensuration data and volume tables are lacking.

4 Quality assessment

41 Preliminary remarks on quality assessment

411 Definition of quality assessment in a forest inventory. The previous sub-chapter dealt with the methods used in a forest inventory to estimate objectively gross volumes of the trees within the sample (total gross volume, or gross volume of the bole, or up to a minimum diameter), these volumes being afterwards expanded to the whole inventoried stands according to the sampling design used. Each tree or part of a tree has, in addition to its dimensions, other characteristics such as shape, aspect, defect and decay, which make its wood more or less useful and valuable for given purposes. The classification, quotation or quantification of these characteristics and the recording and processing of the corresponding data - which constitute quality assessment - are thus necessary to provide the users of the inventory results with more meaningful and detailed information.

412 Assessment of "net volumes" and usefulness of this concept (with special reference to forest inventory of mixed tropical hardwoods). Very often external defects of the standing trees are classified in two main categories - those which are acceptable with regard to a given type of utilization of the wood and those which make the corresponding portion of the tree unusable for this utilization. The volume of the parts of the tree with this class of defect - "defective parts" - and sometimes of the whole tree itself are subtracted from the gross volume and the reduced volume is called the "net volume" (see paragraph 31). In many inventory reports estimates of "net sawnwood volumes" or "net plywood volumes" are thus obtained by deduction of portions classified as defective for sawnwood or plywood production from the corresponding gross volumes. Although this is a common procedure, the validity and usefulness of the concept of "net volume" are doubtful in the case of inventory of mixed tropical hardwoods, for the reasons given below.

There is always a subjective component in quality assessment, which must be reduced to a minimum by a good classification and quotation of the defects. This is particularly important in tropical forestry since the inventory people are most often on the management or ownership side and not on the wood utilization side. Net sawnwood volumes given by the inventory may not correspond to the volumes effectively used for sawnwood.

Even if we consider as negligible the bias coming from the viewpoint of the inventory people, there are other reasons why the so-called net volumes are significantly different from the volume of usable material, among which can be quoted:

- quality assessment of standing trees most often does not take into consideration the inner defects which are not visible and which cannot be safely predicted and precisely estimated from external observation; even for the external defects quality assessment may be invalidated by difficulty in evaluating the defects on the upper part of the tree;

- in most of the mixed tropical hardwoods there is an incomplete knowledge of site quality and environmental factors which may have a bearing on wood quality; this situation is different from that of many European forests which have long been known in detail by the foresters and the loggers: assessment of a precise percentage of logging losses and rejected wood is much easier in these stands;

- there are rapid and significant changes in the conditions of utilization of tropical hardwoods (changes in the domestic and international markets with lower qualities being accepted when demand is high, modifications in the local wood processing facilities, mechanization and changes in the sizes and practices of the logging units, etc.): thus the specifications of the defective volumes used for assessing the net volumes may not be applicable one or two years afterwards, and differences between "net volumes" and usable material may increase even more.

For all these reasons - and as already mentioned in paragraph 31 - assessment of "net volumes" does not appear to be of very great help in mixed tropical hardwoods, at least in economic terms. Nevertheless this must not be considered as the only purpose of quality assessment which has other useful applications in forest inventory.

413 Other applications of quality assessment in forest inventory.

Comparison of the qualities of the same stand at intervals

Quality assessment is useful for controlling (or "monitoring") the growing stock. In repeated inventories of a given forested area, quality assessment makes possible a study of the evolution of the stands with regard to the quality characteristics and the defect occurrence. For such a comparative study, and provided that the quality classification of the standing volumes is meaningful, the equivalence between the volume of the

"non-defective" classes and the usable material is not required; what is important is that, for instance, a better "score" in the second inventory as compared to the first inventory means a real improvement with regard to quality characteristics and defect occurrence.

Comparison of qualities for several stands

Quality assessment is also useful for comparing two or more inventoried areas. Here too, there is no need for an equivalence between the volumes of the "non-defective" classes and the usable material, but the quality indicators must be relevant.

Stratification of the standing volume for further studies

The stratification of the standing volumes into different quality classes may be useful in estimations related to quality. This is particularly so in the case of the assessment of a "recovery factor" (or "conversion factor" or "utilization factor"), i.e. the ratio of the usable (or "extractable", or "commercial") volumes to the corresponding inventory volumes (gross or possibly net volumes). The conversion factors of the various classes are in general significantly different, if the quality classification is meaningful, and the estimation of a global conversion factor is thus improved by the quality classification.

Some indications of the assessment of recovery factors are given below in subchapter 5 "Recovery studies".

42 Methods of quality assessment

For the sake of presentation, these methods can be divided into methods of assessment of external characteristics and defects and methods of assessment of inner defects. External characteristics and defects can be recorded on standing trees as well as on felled trees whereas the estimation of inner defects on standing trees can be made only through partial and somewhat imprecise observations.

In a particular forest inventory there may be quality assessment (external and possibly internal characteristics and defects) on all trees of the sample (or of a sub-sample) and quality assessment on a small subsample of felled trees which may be the sample trees for the volume equations. Regression analysis between the two corresponding categories of data can then be used to improve the quality data obtained from the observation of the standing trees. There may be additional quality indicators recorded on the felled trees, but for the common ones the system of quotation or quantification and recording must be the same to permit the comparison of the data from standing trees and from felled trees.

421 Assessment of external characteristics and defects

421.1 Recording unit of assessment

For assessment of external characteristics and defects on standing trees as well as on felled trees two basic approaches may be adopted:

1) the section concept: the stem is divided into a number of sections, each of an absolute, relative or variable length, the quality of each section being assessed separately;

2) the tree concept: the stem is classified according to a series of selected quality or defect classes.

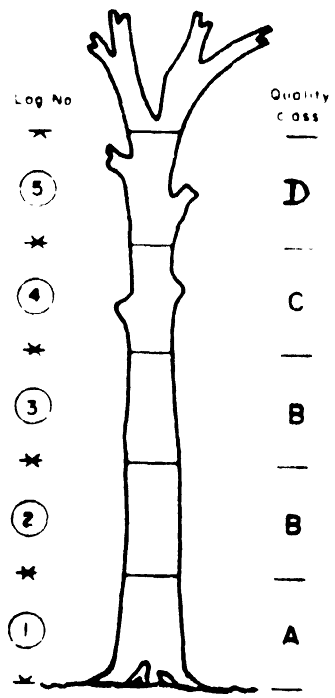
421.11 **The section concept**

a) **Sections of absolute length**

The length of the sections in a stem remains constant according to chosen specifications depending on local requirements (see Figure V-2). A standard log length of five metres, or about 16 feet, is often used as the length of a section. The gross volume of each section is assessed either by means of taper functions, or on the basis of a percentage of the gross volume of the total stem derived from the sample trees used for the formulation of the volume equations, or possibly by measuring the diameter at the mid-point of the section. Care is necessary to allocate defects to the appropriate sections.

Figure V -2

Quality Assessment - Constant Sections

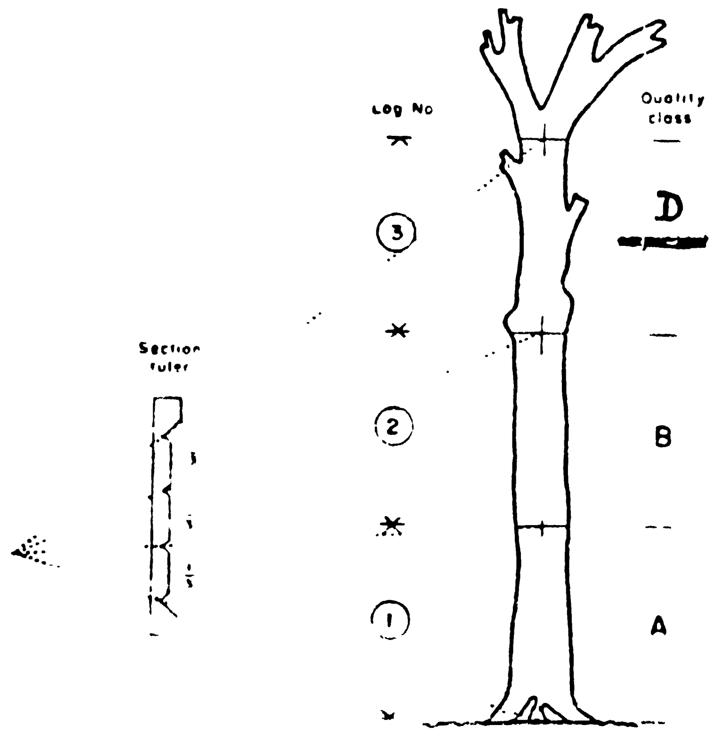


b) Sections of relative length

Quality assessment by dividing the stem into sections of relative length is illustrated in Figure V-3. In this method the number of sections in the stem remains constant, while the length of each section varies in accordance with the length of the stem. Section limits are determined by using a section ruler. This instrument may be used independently of the distance between the tree and the observer. With increasing number of sections, quality assessment under this concept becomes correspondingly more detailed and time consuming and also less reliable as the allocation of defects to the appropriate sections becomes more difficult. Figure V-3 shows a division into three sections, a number which might permit good progress of work without losing too much of the indicative nature of the results. The gross volume of each stem section is estimated from taper functions or from the data of the sample trees used for the volume equations or by direct measurement of length and mid-diameter of each section, this last solution being time-consuming.

Figure V-3

Quality Assessment - Relative Sections



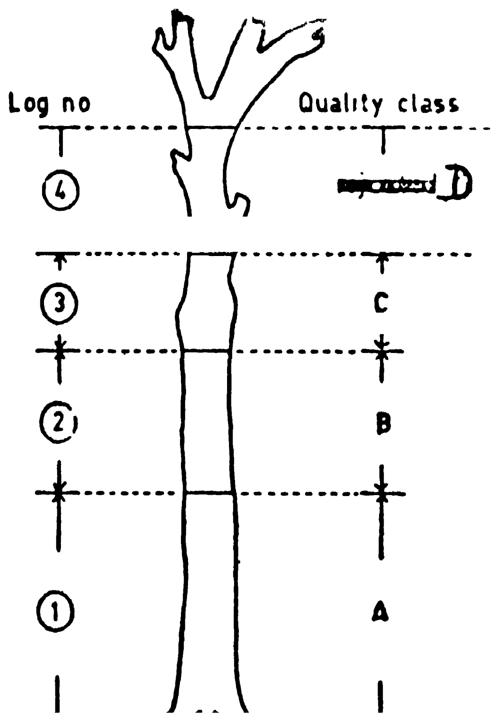
c) <u>Sections of variable length</u>

The division of the stem is governed by the location of the important defects, the purpose being to separate the logs of material deemed usable from the defective portions. This method is illustrated in Figure V-4. The limits of each section would have to be determined by eye using judgement. To determine volumes, the lengths of the sections would have to be determined and taper functions used. If these functions are not available it would be necessary, in addition, to measure end- or mid-diameters of the sections.

This procedure is accurate and practical for quality studies based on measurements of felled trees but its practicality is doubtful if applied to quality assessment of standing trees; it is time-consuming, difficult and entails a great element of subjectivity. Moreover assessment of defective parts and usable parts cannot generally be done with precision, at least in the case of mixed tropical hardwoods as has been shown in paragraph 412.

Figure V-4

Quality Assessment - Variable Sections



421.12 <u>The tree concept</u>

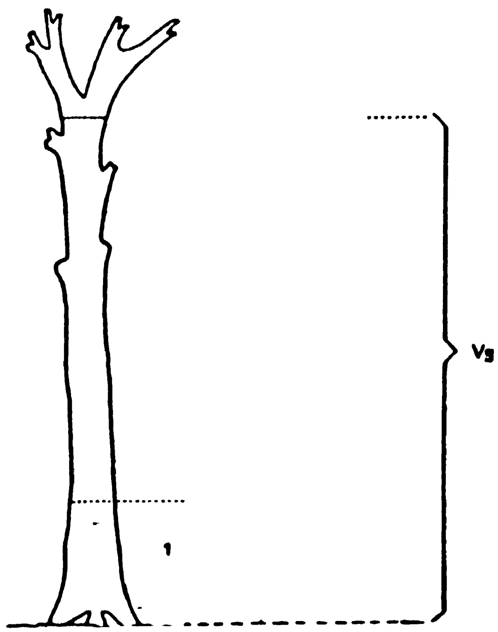
Figure V-5 illustrates the manner in which the tree concept of quality assessment applies the quality of only a specified lower portion of the stem to classify the whole stem. The specified length of this chosen portion of the lower stem does not usually exceed six to eight metres. Usually, only one specified length is used for each inventory though, in some instances, it may be necessary to specify lengths according to species. In buttressed trees the specified length is applied to the trunk above the buttress. Volume is presented as total volume of the tree. In general, the lower portion of the stem contains the greater part of the total volume and is the part of the tree of greatest potential value.

The advantages of assessing quality by the tree concept, as compared with the sectional concept, are:

- quality class specifications may be determined most easily on the lower portion of the stem;
- the possibilities for subjective bias are reduced;
- the method is more rapid;
- the results of the quality assessment studies can also be presented in the form of stand tables;
- volume estimation is simpler.

<u>Figure V-5</u>

<u>Quality Assessment - Tree Appraisal</u>



<u>Remark</u>: The quality of Log No. 1 may be assessed from a number of specified quality classes. The tree as a whole takes its quality from the quality classification of Log No. 1.

421.2 Quotations

Once the gross volume of a "recording unit" (tree, or section of a tree) has been determined, it has to be classified in one of the various quality classes. The size and number of quality classes must be decided carefully, taking into account the purpose of the quality assessment exercise, the increased risks of subjectivity inherent in a detailed classification and the relatively sparse information obtained from a very broad classification.

The allocation of the volume of a recording unit to a given quality class can be done in a global way, directly from a global appraisal of the various characteristics and defects, or in an analytical way by evaluating separately the different types of defect and subsequently regrouping the corresponding quotations for the final allocation of the unit to one of the quality classes.

An example of the first type of assessment is often used in simple classifications on a tree concept, such as "trees rejected" and "trees not rejected", or "sound", "defective" or "dubious". The second type has been used in West Africa with classification on the basis of sections of relative length, the defects being regrouped in three categories: those related to the shape of the section (bends, crooks, oval cross-section, etc), its healthiness (broken branches, rotten knots, etc.) and the aspect of its wood (grain, scars, twist, sound knots, etc.); each section is ranked from one to five within each of the three defect categories and then these rankings are combined to form a range of five global quotations for the whole section.

A thorough analytical appraisal is, however, to be preferred to the global approach, which is more liable to subjective bias. The number of rankings of the quotation must be large enough to allow for detailed evaluation and at the same time small enough to make the exercise as reliable as possible. Five steps appear to be an acceptable compromise.

421.3 Some recommendations for the assessment of external characteristics and defects in forest inventory

If quality assessment is to be made on a subsample of trees from the whole inventory sample, the selection of these trees must be made on a purely objective basis. Any systematic procedure such as "one subplot in every sampling unit" or "one sampling unit every n^{th} sampling unit", or "each i^{th} tree within each sampling unit" is recommended insofar as it does not entail any other bias.

Subjective bias in quality assessment can be reduced by several means, such as a very clear and comprehensive "quotation key" in which every defect is mentioned with possible degrees of gravity and corresponding quotations. It is preferable to ask the field crews to record single defects and their degrees of gravity separately and to apply the corresponding quotations only in the office, especially when these quotations result from a combination of several defects. To make the quotations more reliable and more homogeneous it is important to restrict the number of people in charge of the quality assessment work and to train them very thoroughly. The work should be done by one man per crew, preferably the crew leader.

The use of binoculars is recommended for the observation of the upper sections of the standing stems when the section procedure is used. The observer must turn all around the trees, and at a certain distance, in order to make a full inspection; this latter requirement is fundamental but is not always fulfilled in inventories of mixed tropical hardwoods where access is often difficult.

422 Assessment of internal defects

422.1 Assessment of internal defects on felled trees

The internal defects are evaluated on stump cross-sections or breast height cross-sections and possibly also on other cross-sections. Volume of rotten parts and consequently of sound volume can thus be estimated precisely. The most important problem is how to quote, combine and enter in the classification other internal defects such as insect damage, eccentricity, stains, splits, etc. Here, too, a satisfactory quotation key has to be devised whereby the various defects and their different degrees of gravity can be combined. Applicability of existing grading scales is worth testing.

422.2 Assessment of decay in standing trees

In recent years, electrical or mechanical drilling instruments have been used to determine and measure decay at breast height in standing trees of mixed tropical forests. Results of these observations have shown that decay occurrence at breast height can be detected with sufficient precision (relatively few trees with a very small decay or an eccentric decay are wrongly classified as trees without decay at breast height). However, precise estimation of the extent of the decay at breast height appears not to be feasible, at least in certain forests; eccentric and irregular shape of the trees and of the decay, prevent this. Moreover, in some cases there is only a very loose correlation between diameter of the decay at breast height and its length, so that a direct and reliable estimate of the volume of the decay and consequently of the sound volumes appears impossible. Finally, problems are caused by the occurrence of high buttresses and of upper decay.

However, observations showing the mere presence of decay at breast height are very useful. They provide an indicator of decay occurrence in a given forested area, which allows for comparison with other forests. They also permit a stratification on a tree basis of the standing volume into quality classes (such as volumes "without decay at breast height", "with small decay at breast height" and "heavily decayed at breast height") which can be used for further studies and especially for the assessment of recovery factors.

5 Recovery studies

51 Principle

Regarding volumes, the usual results of a forest inventory are gross volumes up to a given diameter, expressed per diameter class and group of diameter classes, per species, and per quality class, for each inventory unit or stratum within this inventory unit. For some important end-uses, such as sawnwood and plywood, these gross volumes represent an overestimation of the actual usable volumes, i.e. of economic value and which have to be considered in preinvestment studies and also in national and subnational economic and planning programmes. Therefore it is necessary to obtain an estimate per species or group of species and per inventory unit of the ratio between the volumes which are likely to be extracted and the gross volumes given by the inventory , taking into consideration the prevailing conditions of forest management, of logging, of accessibility and infrastructure, of wood utilisation and of domestic and international markets. Too often there is strong criticism of inventory documents in tropical countries because the information produced by these expensive operations is not of direct use for the economic and planning purposes which should be one of their main objectives. As it is necessary to get an estimate of the usable wood, economists and industrialists are applying an arbitrary ratio to the gross volumes (or the so-called "net volumes") which is seldom valid.

Recovery factors are also useful for the owner and the manager of the inventoried forests. From the market prices of the usable wood he can determine, by the use of the results of the recovery study the price at which he can "sell" the standing volumes, taking into consideration the logging and transport costs. More generally, the information provided by a recovery study is useful for the owner or the manager of the forest when dealing with the logging contractors.

The question has been raised as to whether the estimation of these ratios should be provided by the inventory people or whether it should be left to others such as economists or logging specialists.

It seems obvious, however, that the people responsible for the inventory work are the best acquainted with the figures they produce, with their validity and their applicability, and that they should therefore be involved in the estimation of these ratios, either by themselves or preferably in cooperation with logging and other specialists.

Studies related to the estimation of these ratios are called here "recovery studies", but their principle is the same as for those called in other documents "forest utilization" studies or "harvesting intensity" studies.

52 Related problems

In addition to the estimation of the extractable volumes (or of the parts of the gross volumes which are left in forests), it is also interesting to know the percentage of each commercial grade of the extractable volumes, as the respective value and possible utilisation of the various grades are different. A recovery study should aim at estimating these percentages, although in some cases grading is not as objective as it could be.

The extractable volumes to be considered are those which come to the mill yards if the wood is to be processed locally, or to the harbours if it is to be exported. In the case of domestic processing the conversion factor of the mill is applied to the extractable volumes given by the inventory in order to relate the output of the mill to the existing volumes in a given forest area.

Due to the changing conditions in wood utilisation, in markets, in infrastructure and possibly also in forest management and logging, the results of a recovery study are valid for a relatively short period and must be up-dated when significant changes occur. Even within a given region or country the recovery factors vary according to accessibility and to the possible utilisation of the forests; it is of utmost importance to distinguish, for instance, between the case of a forest used for pulp production and that of a forest used for sawnwood and plywood production, or between the case of local processing and the case of log export.

In mixed tropical hardwood forests, recovery studies must be performed by species or groups of species of the same utilisation destination. In most cases a recovery factor covering all species or very large groups of species is meaningless as there may be tremendous differences in recovery and in value per volume unit within these groups.

53 General procedure

531 Main steps of a recovery study

In mixed tropical hardooods the recovery studies can be split in three main parts:

- estimation of the selection of the standing trees; if for certain species all trees which can be logged according to the management regulations are effectively felled, for many others there is a selection of the standing trees, for instance those which are

assumed to be rotten inside after tapping the bole with a hammer are generally not felled;

- estimation of the percentage of trees felled but not used due to splitting, breaking, significant decay not detected previously, bad logging conditions, etc.;

- estimation per inventory quality class of the percentage of rejected volumes and possibly of percentages of the different commercial grades and further determination of the global recovery factors and grade percentages for the whole gross stock.

532 Implementation

If logging units do not exist in the inventoried area or in a similar neighbouring area, an experimental logging operation may be carried out. This solution is expensive but allows for an easier planning of the study. In this case, however, the logging is not necessarily included within the commercial process and the output of the study may be optimum recovery factors.

If a survey of logging units is carried out, the sample of these units will have to be carefully constituted and stratified according to the main utilization destination of the extracted wood (e.g. local processing or log experts, pulp or other industrial uses) and possibly also according to the logging system used and to the accessibility if this varies significantly from one part of the inventoried area to the other. The most evident procedure within a logging unit seems to be:

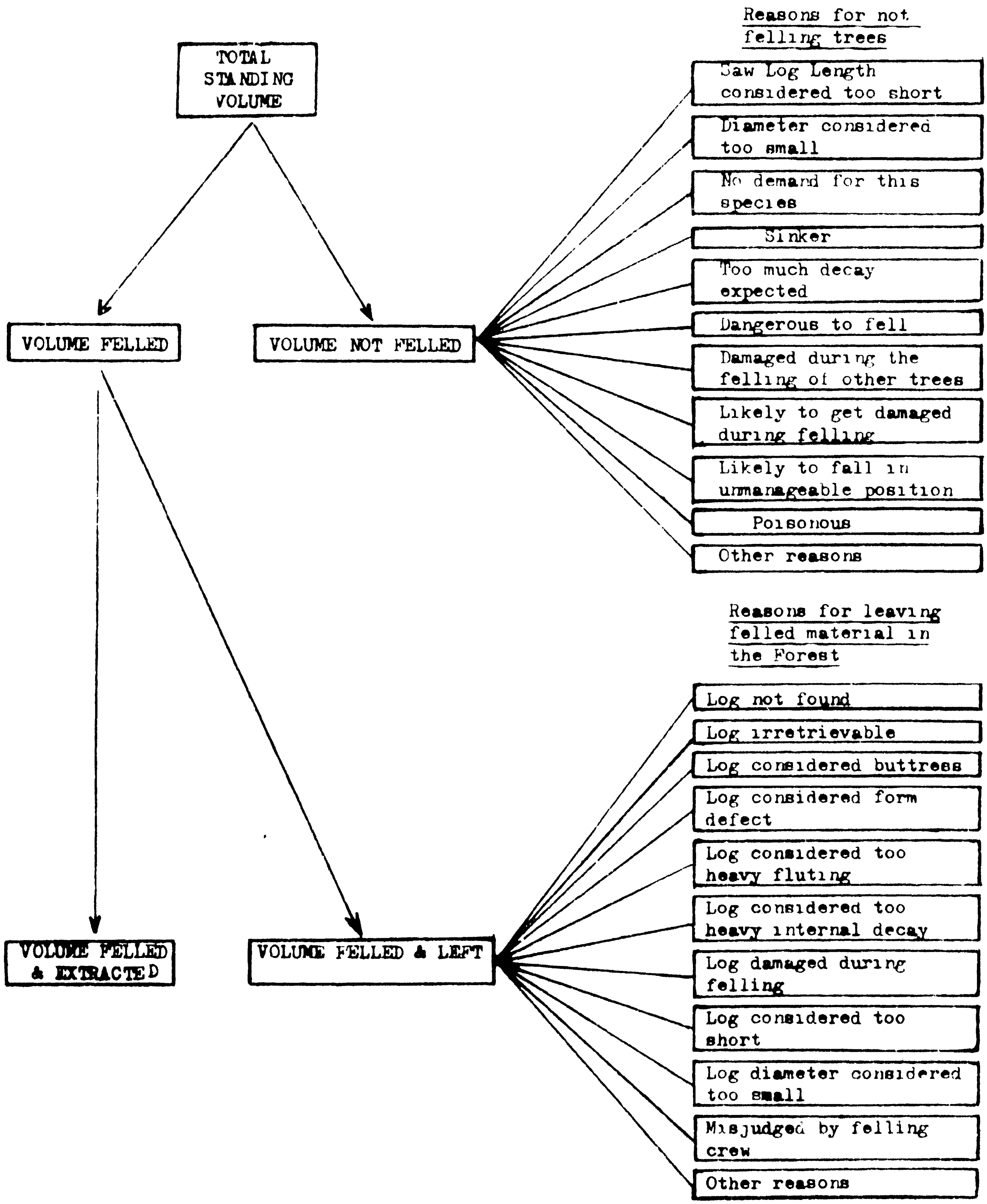
- before logging, the full enumeration and numbering of all trees of the studied species above the minimum acceptable diameter, with estimation of their gross volumes and with quality assessment, in an area which is soon to be logged;

- after logging, the counting of abandoned standing and felled trees and the measurement of the extracted logs and logging losses and waste.

Recording and processing of the data (with possible use of multiple regression analysis between inventory quality classes and commercial grades) has to be designed carefully. The total cost of a consistent recovery study is not negligible, and its programming and budgeting must be included in the planning stage of the inventory.

533 Example

The following graph illustrates the principle and the procedure for a recovery study. It is adapted from a similar graph drawn for a recovery study performed within the framework of an FAO/UNDP inventory in hill dipterocarp forests of Sarawak.


TOTAL STANDING VOLUME
VOLUME FELLED
VOLUME NOT FELLED
VOLUME FELLED & EXTRACTED
VOLUME FELLED & LEFT
Reasons for not felling trees
Saw Log Length considered too short
Diameter considered too small
No demand for this species
Sinker
Too much decay expected
Dangerous to fell
Damaged during the felling of other trees
Likely to get damaged during felling
Likely to fall in unmanageable position
Poisonous
Other reasons
Reasons for leaving felled material in the Forest
Log not found
Log irretrievable
Log considered buttress
Log considered form defect
Log considered too heavy fluting
Log considered too heavy internal decay
Log damaged during felling
Log considered too short
Log diameter considered too small
Misjudged by felling crew
Other reasons

6 Accessibility studies

61 Introduction

Subchapters 1 to 5 deal with the production of volume estimates in a forest inventory from data collected in the field. In addition to the quantity and quality of the standing and extractable volumes, knowledge of the physical and socio-economic parameters which have a bearing on the forest management and harvesting costs is necessary. These parameters define the accessibility of the standing volumes and future yields of the inventoried forests.

Assessment of the accessibility parameters should be carried out within the framework of the inventory for many reasons:

- the inventory results must be as complete and meaningful as possible and must therefore include data on accessibility in order to give information to the users of the inventory which can be directly and immediately utilized by them;

- the inventory crews are collecting data in a large number of units objectively located over the whole inventoried area, and are thus in a better position than most of the users to record also accessibility data, particularly as it may be appropriate for further computations to have accessibility data and volume data recorded entirely or partly in the same sampling units;

- it is much more practical and economical to have accessibility data recorded by the inventory crews than to perform another survey designed only for collecting this additional information.

Information on accessibility is, like that on volume estimates, needed at different scales and levels of precision depending on the type of results required. The method used for assessing accessibility will vary accordingly. However a standardized approach, which unfortunately does not exist at present, would greatly facilitate the comparative use and interpretation of accessibility results.

For a given level of the forest inventory (world, regional, national, subnational, preinvestment or local level) and a given level of precision, the accessibility study can be defined as providing an answer to the following question (Nilsson, 1972).

"How much wood specified by species, dimensions and qualities can be made available at tentative markets (mill sites) within alternative cost limits per unit volume ?"

Given this definition, possibly complemented by the introduction of the time factor, the method used for assessing accessibility in a given forest inventory must solve the following problems:

1) Which parameters need to be collected ?

2) How can these parameters be quantified or classified ?

3) Which quantitative relationships have to be used to estimate the management and extraction costs from these accessibility parameters ?

It is clear from the above considerations that a permanent dialogue between the inventory and the logging specialists must be maintained in order to design a suitable method of accessibility assessment within a given forest inventory. This is particularly true for the problems of the selection and quantification of the accessibility parameters, whereas the third problem lies essentially within the competence of the logging specialist. In the following paragraphs we will deal only with the selection and quantification of accessibility parameters.

62 Selection of accessibility parameters

621 The cost of logging, transport and forest roads varies according to an almost infinite number of factors. Some of these have a strong influence, whereas other are of only minor importance and can therefore be disregarded for the purpose of assessing accessibility. The practical approach is, then, to establish the correlation between the selected factors and the logging and transport costs. This can now be made by logging specialists in various ways, the most practical being to set up mathematical models for each work operation quantifying the influence on the cost of the selected factors. In such model building the logging specialist should endeavour to make use of parameters which are already measured in the inventory and should be rather cautious in introducing additional parameters which might be difficult and costly to measure by the inventory crews. The advantage of the use of mathematical models is that they can be included in the computer programmes of the inventory, thus enabling the accessibility of the inventoried forests to be assessed simultaneously with the inventory results on the quantity and quality of the resource.

The accessibility parameters can be classified mainly into two groups, namely the forest condition parameters and the socio-economic parameters.

The values of these parameters for a given inventoried forest or for a part of it have to be combined with production data in the mathematical models for the assessment of the management and harvesting costs. These production data have to be determined for the various forest work operations (mainly logging, transport, road construction and maintenance) from work studies and production and cost control schemes.

Other classifications can also be applied to accessibility parameters. It is important, for instance, to distinguish between those of a stochastic nature (e.g. volumes by diameter classes) which are estimated by field sampling and those of deterministic nature (e.g. the distance of an inventoried stand from mill site or market). The latter are usually not measured in the field. Whether a parameter is to be assessed by a sampling procedure or by a deterministic method depends on practical factors.

Like other parameters (see paragraph 221 of Chapter 3) accessibility parameters can be given continuous or discrete values through direct measurements or can be assigned to a given class (especially in the case of descriptive or qualitative parameters).

622 <u>The forest condition parameters.</u> The forest condition parameters are physical parameters related to the trees, to the stands and to the land, to the climate and to the location (with regard to existing or possible access to the forest).

Most of the tree and stand parameters are generally estimated by field sampling procedures and many physical data on the land can also be collected during the forest inventory. It is important that the forest inventory data be collected in such a way as to enable the results to be applied to exploitation area units. Their precision is dependent on the sampling intensity of the forest inventory in relation to the size of the exploitation unit. Data obtained from low sampling intensity over a large area can give accurate estimates for the whole area, but do not generally give sufficiently accurate data for the assessment of logging costs for parts of that area. Apart from the sampling intensity the distribution of the sample has also to be considered. A systematic one-stage sampling design is often considered useful as it allows for the possibility of changing the limits of the exploitation units.

622.1 Tree and stand parameters

These are estimated in all forest inventories and are mainly numbers of stems and the corresponding gross or net volumes per diameter (and possibly height) classes, and per species or groups of species. The mean and total estimates must be given with sufficient precision per exploitation units if they are to be used for assessing accessibility.

They include also parameters of quality (see subchapter 4) which are to be estimated to determine the percentage per species (or groups of species) and per size classes of the trees which will not be felled due to their visible defects and which also serve for estimating the extractable volumes by means of a recovery study.

The results of the recovery study (see subchapter 5) also provide physical data essential for the accessibility study. Since they are collected in logging units, it is possible to find out which volumes are to be considered in each logging operation (felling skidding and truck hauling).

Other tree and stand parameters are important with regard to accessibility but are difficult to quantify, such as the thickness of the undergrowth or the branchiness of the trees.

622.2 Terrain and soil parameters

The main characteristics of terrain and soil which have an influence on forest accessibility are considered in the "IUFRO proposal for international system of terrain classification" and in the FAO note "Tentative checklist for describing and quantifying logging transport and roading conditions". These are:

a) terrain parameters

- terrain pattern which can be described by geomorphological features such as relief amplitudes, regular or irregular drainage pattern, stream frequencies, rock outcrops, etc.;
- area of a single physiographic feature ("terrain unit") defined by its relief amplitude, its length and width;
- width and depth of rivers and creeks;
- slopes (longer than 50 metres);
- ground roughness defined by the frequency of obstacles with a relief amplitude exceeding 0.3 metres;
- microtopography defined by the frequency of gullies and slopes shorter than 50 metres;
- area flooded with an indication of the duration and frequency of the floods;

b) soil parameters

- bearing capacity in moist state for off-the-road vehicles;
- suitability for road construction and maintenance which takes into account the depth and the texture of the soil and the stoniness of the surface (1);
- susceptibility to erosion which is important when considering in particular the road construction and maintenance costs.

622.3 Climatic parameters

The climatic parameters useful for assessing logging costs are related to the following items:

- rainfall, the corresponding characteristics being the amount and the distribution of annual rainfall and the maximum rainfall per hour and per day;

(1) Deposits of gravel and quarry sites should also be recorded by the inventory crews outside the sampling units, especially when such deposits and sites are rare.

- water discharge and its variation;
- temperatures;
- insolation, with the important characteristic of the length of sunny periods during the rainy season.

622.4 Location and access parameters

The main location and access parameters useful for accessibility assessment are:

- distance and transport routes to wood-using centres (mills, cities, densely populated areas, export ports);
- data concerning the existing and potential transport network inside the forests, such as the network density and the distance of cross-country transport per types, standards and capacity classes (estimation of the road length can be made through the use of a rectangular transect system and the application of the "needle problem" method).

623 The socio-economic parameters. These parameters are absolute and are determined by the national economy and laws. They are needed to establish cost per unit time of production factors in the cost formulas. Three groups of data can be distinguished here: labour, equipment, and other data.

Labour: Information on labour availability and skill, payments, fringe benefits, transport or camp facilities, number of working days per year, number of effective working hours per day, etc.

Equipment: Operating costs based on purchase prices, customs duties, cost of fuel, facilities for and cost of servicing, etc.

Other data: Such as laws on transport, railway tariffs, exploitation restrictions, composition of the enterprise, etc.

63 Quantification and/or classification of accessibility parameters

631 Parameters relevant to felling. For felling, in addition to the most important tree characteristics, other parameters such as crown length or any other indicator on branchiness and on delimbing difficulty is useful. Slope and other terrain conditions are also important. A combined quantification of the form and quality of the trees and of the terrain and vegetation on the felling site is shown in the following table. The coefficient should reflect how production is influenced in relation to "normal" conditions.

Correction factor reflecting working conditions (other than normal)

Terrain and vegetation on the felling site	Form and quality of the trees		
	Tall and well formed trees and/or few damages	Normal length and form and/or normal damages	Short and badly formed trees and/or severe damages
Steep terrain (more than 30%) or swampy ground and/or severe felling obstacles (underbrush, etc.)	0.9	0.8	0.6
Average - normal - conditions	1.2	1.0	0.8
Smooth or undulating terrain, well drained soils, no severe underbrush or other felling obstacles	1.5	1.2	1.0

632 Parameters related to transport and road construction

632.1 The following classifications of slope and ground roughness are extracted from the IUFRO "Proposal for International System of Terrain Classification" and are given as examples but not as models to be adopted in all cases.

632.11 Slo

Slope is described by the gradient (a), the length of the slope (b) and the aspect of the slope (c).

Slopes with lengths of more than 50 metres are defined as major slopes. Slopes with lengths of 10–50 metres are defined as minor slopes, for example lesser valleys and hillocks. Variations of less than 10 metres in length are defined as "ground roughness".

(a) Gradient

The average gradient is recorded in per cent. The following classes are adopted:

1. 0 - 5 %
2. 5 - 10 %
3. 10 - 20 %
4. 20 - 33 %
5. 33 - 50 %
6. > 50 %

Intermediate classes may be used if necessary.

The slope is stated in terms of its relation to the access road as

1. positive (uphill to reach the access road)
2. negative (downhill " " ")

The description may be completed by recording the maximum gradient.

(b) Length of the slope

With regard to major slopes the length of slope is recorded in metres in the following classes:

Minor slopes

1. 10 - 50 m

Major slopes

2. 50 - 100 m
3. 100 - 200 m
4. 200 - 400 m
5. 400 - 600 m
6. 600 - 800 m
7. 800 - 1000 m
8. 1000 - 1200 m
9. 1200 - 1500 m
10. > 1500 m

Classes with wider intervals may be obtained by amalgamation. Minor slopes may occur also as parts of a major slope.

(c) Aspect of the slope

The aspect of the slope is recorded as the compass bearing in the following way:

1. North (N)
2. Northeast (NE)
3. East (E)
4. Southeast (SE)
5. South (S)
6. Southwest (SW)
7. West (W)
8. Northwest (NW)

632.12 Ground roughness

The roughness of the ground is described independently of the slope on the basis of the occurrence of obstacles, i.e. local surface variations, boulders, rocks, stumps, holes, hollows, etc. of more than 30 cm height or depth.

The roughness is described by the general occurrence of obstacles (a). When required a description of the occurrence of obstacles by types and size is undertaken (b).

(a) General occurrence of obstacles

The following classes are adopted:

1. very smooth ground; average distance between obstacles $>$ 5.0 m; minimum distance between obstacles $>$ 3.0;
2. smooth ground; average distance between obstacles $>$ 5.0 m; minimum distance between obstacles $<$ 3.0;
3. uneven ground; average distance between obstacles 5.0 - 3.0 m;
4. very uneven ground; average distance between obstacles $<$ 3.0 m;
5. ground with boulders and scree;
6. ground with precipices and clefts.

By distance between obstacles the unencumbered distance between the limits of the obstacles is understood.

(b) Occurrence of obstacles by types and sizes

Height or depth of obstacles, metres	Number of different types of obstacles					Total number of obstacles per hectare
	Precipices and clefts	Rock and boulders	Holes and hollows	Stumps	Others	
0.3 - 0.5 0.5 - 1.0 1.0						

The occurrence of types of obstacles should be recorded in absolute figures. With regard to the class "precipices and clefts" the height/depth class may be sub-divided.

Problems related to slope assessment.

The slopes considered the most important with regard to logging costs are slopes on distances longer than 50 metres ("major" slopes). In the field inventory the slopes can be measured generally only on shorter distances (10 to 20 metres in many cases). Mean slopes longer than 50 metres can be estimated on a sampling basis on aerial photographs or on good large-scale (smaller than 1/25,000) topographic maps. The comparison between measurement of slopes on the ground and on the photographs or maps shows that the occurrence of steep slopes is overestimated on the ground, since a certain proportion of steep slopes in the terrain are on short distances.

Whatever the gradient classification adopted, 50% (practical maximum slope for a tractor at present) and possibly 70% (occurrence of difficult road construction problems) should be used as limits in the gradient classification.

A recommended classification of lengths of slopes with a gradient larger than 50% is:

50 metres - 300 metres

300 metres - 700 metres

> 700 metres

632.3 Another example of ground roughness classification

A further method of recording ground roughness together with some other factors difficult to measure is shown in the following table. Each parameter is subjectively assessed in a difficulty class ranging from 1 to 5 where difficulty class 3 could be regarded as "normal". The points of the difficulty parameters are added and the sum is then an expression on their aggregate influence on extraction to be used in the cost formula for this operation.

Difficulty class	Parameter				
	Surface structure	Ravines and swamps	Soil bearing capacity	Undergrowth	Windfalls etc.
1	smooth even 0	none 0	good 0	none 0	none 0
2	2	1	1	0	0
3	4	2	2	1	1
4	6	4	3	2	1
5	very rough many stones and boulders 10	high frequency 8	very poor 6	very dense 4	high frequency 2

The sum of points Σ out of table gives E through the following conversion table:

E	1	2	3	4	5
Σ	0-5	6-11	12-17	18-23	23-30

CHAPTER VI

DATA RECORDING AND PROCESSING IN FOREST INVENTORY

CHAPTER VI

DATA RECORDING AND PROCESSING IN FOREST INVENTORY

Introduction

Data recording and data processing can be viewed as major links between the planning and completion of a forest inventory. The basic inventory data, either gathered in the field, from photo interpretation or from other sources, cannot be processed without having first been recorded, edited and condensed. In addition, the data processing procedure must be adapted to the specific requirements and design of the inventory itself. It is, therefore, essential that the treatment of the data be considered as an integral part of forest inventory from the very beginning planning stages.

Data recording and processing should be given careful consideration, particularly during the initial planning stage of a forest inventory, since the means of data processing (e.g. available facilities and personnel for computation) or the cost may have considerable impact on the design, intensity, and timing of the entire inventory. Within the framework of information required and money and time available, the treatment of the data has to be considered as a limiting factor which directly influences the choice of inventory method. Broadly speaking, the simpler the inventory design, the lower the cost of data handling and the less time-consuming the job. Although data processing serves more as a tool of forest inventory than as a determining factor, its influence on the realization of the inventory should not be underestimated.

Since the whole field of data recording and processing is very complex and particularly fast-developing, the contents of this chapter can only be considered as general guidelines for choosing and implementing the appropriate data recording and processing methods for a given inventory. The sub-chapter "Data Recording" is restricted to general requirements for data recording and the means and methods of recording forest inventory information from various sources. In the sub-chapter "Data Processing" the different steps and types of data processing are discussed and some practical aspects with respect to tropical zones are given.

2 Data recording

21 General requirements

Before undertaking the design of any "recording document"[(1)], attention should be drawn to the specific data to be recorded. Keeping in mind the simple rule that results to be obtained by means of data processing can never be better or more reliable than the basic input data itself, a determined effort should be made to improve the quality of the data to be recorded. One of the main requirements for reliable data is its objectivity and comparability. Since inventory data will generally be recorded by different people under different conditions, any possibility of human influence on the data itself should be omitted. Recording instructions should not allow any personal judgement of the people concerned. Objective quantitative assessment of data should be preferred whenever possible. In cases where coding cannot be avoided (e.g. classification of crown cover into density classes) the recording instructions should define very clearly the coding criteria. Although a refined stratification for a given variable will permit precise classification, the results may be less reliable than those obtained from measured data, because coding may entail personal judgement.

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(1) A "recording document" is any prepared form on which original data will be recorded, e.g. tally sheets. Recording can be done either manually, or automatically by special devices (see para. 23).

To minimize human bias, whenever possible the parameters to be recorded should be measurable parameters (continuous variable). All discrete variables should be recorded using a broad classification (or coding) system, permitting allocations in a given class as objectively as possible. The aim should be to get homogeneous data which could be compared between one "record unit"(1) and another.

The data should be recorded as they are measured and no processing should be done during the recording stage. If, for example, mean diameter of individual trees is needed for future calculation, and is assessed by two or more direct measurements, only direct measurements should be recorded and the mean diameter calculated later. Similarly, when measuring diameters it is better to record actual measurements rather than the corresponding diameter classes. This eliminates the possibility of errors occurring in transferring from measured diameters to classes. Broadly speaking, the simpler the parameters and the method of recording, the more accurate the corresponding results.

One of the most important tasks in this respect is the design of simple and clearly arranged recording documents, easy to handle in the field and easy to fill in. The design of the recording document should aim primarily at facilitating the recording work, and to a lesser extent the later use of this document for processing. This is particularly so since recording work is usually much more expensive and difficult than processing work. Thus, practicability appears to be another requirement of general nature to be considered in data recording.

Before any data recording begins, it is necessary to become acquainted with the conditions under which the work is to be executed and with the actual data itself. First of all, it is very useful to adapt recording to the personnel in charge of it. For instance, a very low level of training or experience may call for a simple way of recording. An example would be use of special tapes for diameter measurement, on which only the diameter class can be read. Environmental conditions, such as weather, terrain or thick undergrowth, can also affect recording in the field. In wet weather, for example, it may be necessary to use waterproof paper for the field sheets.

22 Specific requirements

221 With relation to the type of data. A practical classification of types of forest inventory data is as follows:

- information on the area by interpretation of remote sensing imagery;
- information on the field plots including site, soil and accessibility data;
- tree tally by species and diameter classes;
- measurements on standing or felled trees;
- information on quality of standing timber.

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(1) For definition of a record unit (RU) see paragraph 412 of Chapter III.

Experience from many inventories in tropical zones has led to the general acceptance of four basic types of records in each RU in the field:

For the Record Unit:

1: this form includes the identification of the RU and gives all information on the plot itself as opposed to tree tally, as for instance:

	Plot identification				Stand description			Accessibility data			
Col.	(1)	(2)	(3)	...							(m)

For the tree tally: generally only one of the three following types is used in connection with type 1 in a given RU:

Type 2: the number of trees is indicated in a matrix[1] in which the rows correspond to the species and the columns to the diameter classes:

	Species code	diameter classes								
		1	2	3	4	5	6	7	.....	n
Col.	(1)	(2)	(3)	(4)	(5)					(m)

Type 3: the tree parameters are recorded within a matrix, in which every tree forms a row and the tree parameters the columns.

	Tree No.	Tree parameters			
		dbh	height	species code	etc.
Col.	(1)	(2)	(3)	(4)	.....

Type 4: the trees are enumerated by species and diameter continuously:

	Species code	dbh	Species code	dbh	Species	dbh	etc.
Col.	(1)	(2)	(3)	(4)	(5)	(6)	......

In a given inventory, different combinations of recording may occur. For example, in a cluster sampling, tree-by-tree recording (method 3) may be required in only every fourth RU, whereas in the remaining 3 RU's the trees will only be recorded either by method 2 or 4 above, depending on the procedure selected for data processing.

As for data recording in the office, more sophisticated methods can be used and the recording system can be aimed more at facilitating data processing since the risk of errors is very much reduced.

(1) The word matrix stands for any type of two or several entry table

222 With relation to data processing. The method of data processing to be used will affect the recording only to a relatively small extent. In any case, the data should be written simply and clearly. If the data are to be key punched for electronic processing (EDP), it is more convenient to arrange the data in the punching sequence although this is not essential since it is generally easy for the key punch operator to adapt to a punching plan. In the case of manual processing, data should be arranged in such a way that computing can start immediately without waiting for time-consuming sorting and re-arranging of the data. In this case the fourth method of tree tally should be avoided since a continuous recording of species code and diameter requires a time-consuming re-arrangement of the trees into species/diameter classes and complicates the work. In the case of qualitative data, the coding key for all parameters should be determined prior to recording.

23 Main kinds of data recording

Methods of data recording differ also with the methods of data processing. The most common type of recording, which is applicable to manual data processing or EDP, uses handwritten field documents. The plot information sheet (i.e. Type 1) should always contain the following sections:

1. Description of work: date, field crew, starting and finishing date of plot survey.
2. Identification of plot: inventory unit, sampling unit, plot or point within the sampling unit, etc.
3. Plot criteria: stand description, environment, accessibility, road network.

These groups of data should be clearly defined when designing the sheet, to facilitate quick control and identification in the office. In the case of further punching for EDP, the column numbers can be indicated under the field of the corresponding item on the field form. The total amount of information recorded in the field form may exceed the 80 columns of a punch card (see also paragraph 311).

The transfer of data from field documents onto punch cards is a significant component in the total cost of data processing. Therefore, there is an increasing use of other than handwritten documents which avoid this transfer.

(a) Port-a-punch cards

Data are recorded on pre-punched 40 column cards with a special portable device. They are later read directly by the computer and stored on disks or tapes. This method, used successfully in the Swedish National Forest Inventory, requires skilled personnel in the field. Some trials of this method in tropical forests under difficult conditions were not very successful.

(b) Mark-sensing documents and cards

The basic procedure of this method is to mark with a special device (e.g. pencil or marking ink) within predetermined positions on the cards or sheets the data to be recorded which will be interpreted later by an electronic optical reader. The advantage of using sheets rather than cards is that more data can be recorded on sheets, whereas most cards are more or less limited to a certain amount of data. Trial of this method in one tropical forest inventory was not very satisfactory due to the large size of the RU's and the consequently large number of species and trees which called for several mark-sensing documents per RU. However, in some cases, such as inventories of plantations with easy environmental conditions, these methods should be successful.

(c) Handwritten documents for optical reader

A relatively new method allows handwritten documents to be read by a multifunction optical reader. Reading is performed by an electronic luminous spot scanning system, through which each character is investigated and, in most cases, identified by the "reading ray" tracing in a spiral motion the contours of each character for identification.

This method, used very successfully in forest inventories in West Germany, requires a computer centre equipped with an optical reader, to read the data and store it on disks or tapes. On the other hand, the characters recorded in the field must be written very carefully, following certain standard rules of writing, and must be placed exactly in their appropriate location on the recording sheet. Since misinterpretation occurs relatively often, the stored data must be scrutinized thoroughly by special editing computer routines, specifically designed to locate such errors. Thus the main drawback of this method for use in tropical forest inventory is its sophistication.

Other methods which may be applicable for recording forest inventory data are: machine-typed documents for data occurring in the office (photo-interpretation) or semi-automatic devices such as auto-recording paper tape calipers described by Badan, which automatically record the diameter measurements. In special cases, where increment has to be determined by boring instruments (e.g. plantation inventories in temperate zones),the "Increment core measuring device" after Eklund may be used. With a special set of machines the annual ring information obtained under a microscope is transferred automatically onto punched cards, or onto paper tapes, since this device can be linked to a card puncher.

All these methods mentioned are applicable only when skilled personnel and appropriate equipment are available. In most tropical forest inventories for which these conditions have yet to be fulfilled use of handwritten field documents appears to be the most appropriate way of recording, regardless of the method used for data processing.

24 Some practical aspects of data recording

241 Organization in the field. Once the recording document has been provisionally designed, its usefulness and practicability should be tested during the preparatory phase of the inventory.

The field instructions must be tested as well. They should give details about:

- the composition of the field inventory crew;
- the functions of the crew with regard to data recording;
- the data to be recorded;
- the manner the data are to be recorded on the prepared recording documents.

The field instructions should also give details on how to progress within the RU, on the sequence of tallying tree species and dbh, on the checking procedure during the tally, and any further information which will facilitate the data collection.

242 Preparation for further processing. Before the recorded data can be processed (i.e. punched on cards in the case of EDP or manually processed), two preparatory actions should be taken:

(a) The field documents should be sorted manually into logical order, which is simultaneously a first check on consistency. A check can also be made to verify that no document of a sampling unit is missing.

(b) A visual check of the data itself is advisable to detect inconsistencies which could be cleared with the field crews if they cannot be corrected in the office.

3 Data processing

31 Steps of data processing

311 Data capture. One of the main problems in data processing, especially from the economical point of view, is the arrangement of basic data into a feasible form for further processing. EDP in particular demands practical and efficient methods of data capture, that is the arrangement of the basic data in a computer readable form. Any manual transfer of data between the recording phase and the processing phase should be avoided as much as possible. In addition to the methods described above (see para. 23), there are two main types of data capture used for the transfer of the original data from field sheets to the computer:

(a) Perforated (or punched) paper tape

Although of decreasing importance in forest inventory, paper tape (as used, for instance, in teletype technique) is especially appropriate for the transfer of large amounts of homogeneous data, such as long enumeration lists. Paper tapes adapt well also to automatic data capture, as in the case of continuous recording of climatic measurements at field stations. A drawback of the paper tape method is, however, the relatively troublesome transfer of the paper tape data onto magnetic tape. Special hardware devices and "free format facility" (1) are needed which will be available only at very few computer centres.

(b) 80-column punch cards

The standard size punch card consists of columns and rows, in which the perforations are made at predetermined places by use of special card-punching machines, the keyboard of which resembles a typewriter.

Punching errors during punching operations can be reduced, if not totally avoided, by the use of "card-verifier" machines, on which the punching of the original data is repeated and checked against the punched card.

Although changes in temperature and humidity could affect dimensions and weight of cards, causing warping (relative humidity in card-storage rooms should not exceed 65%), the punched cards are, under present conditions in tropical countries, the most appropriate way of data capture and transfer, since at almost all computer centres punched-card readers are available.

In addition the standard-sized punched cards are adaptable to different makes of computer. As mentioned above, the data is punched on the cards at predetermined places which are specified by the punch card design. Some basic rules for the punch card design which will help to avoid possible errors are the following:

(i) Always use only one card for the storage of a "logical record". In EDP a logical record is the smallest part of a data file which is determined by the logical structure of the recorded data. As an example the logical records for the 4 basic types of records given in paragraph 221 are respectively:

1. the information on a single plot;
2. the information on a single tree;
3. the tree tally for one species (number of trees per diameter class);
4. species code and diameter of all trees, tallied in an RU.

(1) The use of free-format requires special machine-oriented software, which does not need the definition of the format of each record.

If, especially in the latter case, the logical record cannot be stored on a single card, extension cards for this logical record may be used, provided that an extension code is given on the first card.

(ii) The amount of columns to be reserved for one parameter ("item" or "attribute" of the logical record) is predetermined by the largest figure, which can occur for this item. Thus in the planning stage of the punch card design, careful analysis of each item to be stored is necessary.

(iii) The "data fields" (i.e. the number of columns to be reserved for the storage of one item) can follow on the data card one after the other without blank columns in between. All items, regardless of whether there are continuous or discrete variables, should be punched "right justified"(1) in their respective data fields, decimal points not being punched. All items of different logical records stored in a given data field require exactly the same amount of decimals. The identification of the decimals is done later on by a "format specification" within the computer programme.

312 Editing of data. Editing aims at producing from the basic data file a clean data file free of punching errors and other inconsistencies. The different steps of editing are the following:

(a) Sorting of the data

Sorting is necessary because many checks require that data sets be in chronological order. It can be done manually, mechanically or electronically. Mechanical sorting of 80-column punch cards by the use of special sorting machines requires that one logical record be punched on one single card, the hierarchy of sorting being given by the inventory design. First, coding errors within the sequence codes will be detected and corrected. Larger amounts of data require electronical sorting, making use of special SORT-routines, usually provided by the computer manufacturer.

(b) Error detection by checks

We can consider a given data file as a two-dimensional data matrix of the form:

m	X - item of a logical record
n	I - index for the position of the item X within a logical record
X (I,J)	J - index for the position of a logical record within a whole data file
I-1 J-1	n - number of items of a logical record (variables)
	m - number of logical records of the whole data file

Checks can be made:

- on every individual item X (I,J) separately;
- horizontally on the relation between two or more different items of a logical record, e.g. the relation between X(1,J) and X(2,J) or between X(1,J), X(2,J) and X(5,J);
- vertically on the relation between given items of different logical records, e.g. the relation between X(I,2) and X(I,3).

(1) For example, the value 355 is stored right-justified in a data field of 6 digits if it is punched in places 4 to 6 of the data field, places 1 to 3 not being used.

The different data checks common to all inventory data-processing procedures can be grouped generally under the following types of consistency checks:

- control of completeness: aims at checking the completeness of the whole data file at each level of data accumulation. First, it should be checked that no logical record within a data set (record unit, sampling unit, etc.) and no item within a logical record (e.g. diameter for counted trees, heights for measured trees, etc.) are missing. The completeness of data on different unit levels is usually checked by comparing the accumulated number of sub-units (e.g. trees in a plot, or plots in a sampling unit) with the given totals on the unit level, which are either assessed in the field (in the case of tree totals) or given by the inventory design (number of plots per sampling unit, number of sampling units per block, etc.). To avoid under- or over-estimation, completeness checks should be made prior to any later inventory data processing.

- logical and likelihood control: includes all checks on individual items and on the above-mentioned relations of different items, which can be defined logically in view of the record and sampling design. Such checks are:

  - checks of alphanumeric and numeric punches column by column;
  - range of continuous variables by determining minimum and maximum values, between which the value of the variables can vary;
  - possible range of discrete variables, e.g. for established species codes or for codes of vegetation types, etc.;
  - check of horizontal and vertical inter-relationships in the whole data matrix mentioned above, using logical comparisons of the values of the parameters. In the case of EDP, such comparisons can be very efficiently done using "logical operators", available in advanced computer languages (for details see any FORTRAN programmer's guide).

(c) Listing of inconsistencies and correction

In the case of EDP, a list of the detected inconsistencies is printed automatically as well as all the items of the corresponding cards. Corrections of the basic data should be made in close collaboration with the responsible field officer. The cards are punched again with the corrected data and then added to the original data file, replacing the wrong records on the tape or disk files.

(d) Production of clean data file

This data file, which should contain only clean and reliable data organized in the hierarchy of the inventory, serves as input for all generation operations.

313 Data generation. This step of an inventory data processing system includes all operations aiming at preparing the basic data for further computations, and at computing from this data intermediate and definitive results.

The data must be sorted depending on the inventory design, on the type of data gathered in the field (see para. 221) and on the various classifications used (strata and inventory units). At any level of study the following estimates have to be computed and presented in multientry tables, related to species or groups of species and to diameter classes:

- means per area unit (number of trees per ha, volumes per ha, etc.)
- totals (mainly volumes)

  apling errors

The position of every logical data record, therefore, has to be identified within the hierarchy of the inventory and the corresponding data must be weighted accordingly and aggregated within subtotals and totals for the level of study concerned. The final output of the calculations at the different levels of study are generally:

(a) Stand tables: mean numbers of stems per area unit and possibly corresponding totals per strata and inventory units.

(b) Volume tables (derived from volume equations): individual tree volumes by dbh (local volume tables) or more often by dbh and height, per species or group of species.

(c) Stock tables: mean volumes per area unit and corresponding totals, computed from stand tables and volume equations, or from individual tree volumes in the sample.

(d) Corresponding standard errors or sampling errors for given probability levels according to the particular sampling design.

While stand tables can be developed directly from the basic data, according to the sampling design used, special trials have to be carried out to determine a valid set of volume equations. Prior to the calculation of the final regression analysis, many other computations have to be performed on the basic data (which are most often measurement data on felled trees) which we can call "pre-regression studies". They include the computation of the individual volumes of the sample trees, the possible grouping of the data into different groups of species, the drawing of scatter diagrams, the transformation or weighting of variables, the testing of provisional regression models and the comparison of the corresponding regression lines with the basic data. Once these various trials are completed, the final volume equations and the corresponding volume tables can be developed (for more information on volume equations see paragraph 342 of Chapter V).

"Pre-regression" and regression studies can be carried out on electronic desk computers with limited storage facilities. It is more appropriate of course to use large computers, since statistical trials can be carried out much more easily on these machines, especially if a large amount of basic data has to be treated.

Besides the basic calculations mentioned above, there are in every forest inventory some special investigations which have to be carried out according to specific requirements. Examples of such additional results required are:

- specific volumes such as "net" or "industrial" or extractable volumes taking into account information on the quality of the trees;

- accessibility results computed from assessment of accessibility parameters (such as breakdown of the areas by slope classes, soil bearing capacity classes, etc.);

- cost studies, including evaluation of logging and transportation costs. These additional investigations require several rearrangements of the basic data and the computation of intermediate parameters, such as decay indicators.

314 Presentation of the inventory results

314.1 Basic table formats

The results of a forest inventory, regarding both areas and parameters, are regrouped for presentation in tables. Following the 1967 meeting of inventory experts at FAO headquarters, a minimum set of standard tables was recommended which were already reproduced in the first edition of this manual. These minimum tables required by all inventories are listed below.

Table	Title
VI-1	Summary of areas by present land-use and forest classes.
VI-2	Areas by (life zones), inventory classes and administrative units or other specific classes.
VI-3	Present forest areas according to ownership classes, administrative units or other specific inventory classes.
VI-4	Stand table for each inventory class.
VI-5	Total areas, volumes per area unit and total volumes with precision estimates according to inventory units and inventory classes.
VI-6	Volumes according to use classes and species or species groups by inventory classes.
VI-7	Stock tables for each administrative unit and inventory class according to dbh classes.
VI-8	Net annual volume increments for inventory classes by administrative units.

The formats and some explanation of these tables are given in the following pages. As stated in Chapter V, paragraph 32, results should be given also in metric system if the British System is in use in the country.

Table VI-1

of areas by present land-use and forest classes 1/

Existing Land-Use and Forest Classes	2/	2/	2/	2/
	Hectares			
I. **Total Land Area**				
A. **Forest area**				
1. Natural forests				
a. Broadleaved excluding mangroves				
b. Coniferous				
c. Mixed broadleaved and coniferous				
d. Pure bamboo				
e. Mangrove				
f. Coastal and riverine palms				
g. Temporarily unstocked				
2. Man-made forests				
(those divisions of a. to g. which are applicable)				
B. **Other wooded area**				
1. Savannah, open woodlands				
2. Heath, stunted and scrub forest				
3. Trees in lines, windbreaks and shelterbelts				
4. Other areas				
C. **Non-forest area**				
1. Agricultural land				
a. Crops and improved pastures				
b. Plantations				
2. Other lands				
a. Barren				
b. Natural range and grasslands				
c. Swamp				
d. Heath, tundra				
e. Urban, industrial and communication				
f. Other areas				
II. **Water**				
TOTAL - Land and Water				

1/ For details on this classification see Chapter IV, paragraph 23.
2/ If a classification based on vegetation/environment relationships - such a classification in life zones after Holdridge - is not used, then only one column will be shown.

Table VI-2 1/

Areas by (Life Zones 2/) Inventory Classes and Administrative Units or Other Specific Classes

Date of inventory:

Life Zone 2/	Inventory Classes 3/	Administrative Units or Other Specific Classes					Per Cent of Total
		1	2	3	etc.	Total	
		Area in hectares					
	1.						
	2.						
	3.						
	4. etc...						
	sub-total						
	1.						
	2.						
	3.						
	4. etc...						
	sub-total						
	1.						
	2.						
	3. etc...						
	sub-total						
	Total						

1/ This table is to be presented for the whole inventoried area and possibly for each inventory unit.

2/ Life zones are recognised according to the Holdridge System if adopted; if another type of classification based on vegetation/environment relationships is used, specify the corresponding classes; if such classification is not used omit it.

3/ Inventory classes are mainly classes corresponding to existing land use, physiography, accessibility, operability, or any other stratification used in the inventory (see Chapter IV, paragraph 21). If two or more inventory classications are used simultaneously, the table must be split up accordingly.

Table VI-3 [1]

Present Forest Areas[2] According to Ownership Classes, Administrative Units or Other Specific Inventory Classes

Date of inventory:

Ownership [3] Class	Administrative units or other spec. classes [4]										Per cent of total
	1			2			etc.			Total	
	1	2	etc.	1	2	etc.	1	2	etc.		
1. Publicly owned forests											
a. State forests											
b. Other											
2. Privately owned forests											
a. Owned by industrial enterprisers processing forest products											
b. Farm forests											
c. Other											
3. Ownership not yet determined											
4. Total area of forests											

1/ This table is to be presented for the whole inventoried area and possibly for each inventory unit.

2/ Forest areas are those considered under item I.A of table 1. Similar tables can possibly be presented for "other wooded areas" (item I.B of table 1) if deemed necessary, as well as tables corresponding to the sum of the two categories.

3/ Classification of ownership

1.a. Include forest owned by national, state, and cantonal governments, government-owned corporations, and Crown forests.

1.b. Forests belonging to towns, villages and communes and other local authorities. Include any other publicly owned forests not elsewhere specified.

2.b. All forests owned by individuals, families, or corporations engaged in agriculture as well.

2.c. All privately owned forests not included elsewhere, comprising forests owned by institutions (religious, educational, etc.).

3. Forests for which ownership status is in doubt or has not yet been established.

If necessary, the above ownership classes may be further sub-divided to more specifically described local conditions.

4/ If desired, a separate table can be prepared for each administrative unit.

Table VI-4 1/

Stand Table for Each Inventory Class

Administrative Unit (or other specific class): .... **Date of Inventory**: ....

Inventory Class: .... **Area in Hectares**: ....

SPECIES OR SPECIES GROUPS	D.B.H. CLASS CM. 2/			
1				
2				
3				
4				
5				
6				
.				
.				
.				
.				
.				
.				
.				
.				
.				
TOTAL				

1/ This table is to be presented for the whole inventoried area and possibly for each inventory unit

2/ Class limits should be shown for each dbh class in agreement with limits indicated in table of paragraph 242.1, Chapter V.

Table VI-5

Total Areas, Volumes 1/ per area unit and Total Volumes 1/, Precision Estimates for Inventory Units and Inventory Cl

INVENTORY UNIT	INVENTORY CLASSES 2/	TOTAL AREA		MEAN VOL. PER HA 1/		TOTAL VOLUME 1/	
		ha or other area units	PRECISION 95% PROB. ± %	in cubic units per area unit	PRECISION 95% PROB. ± %	in cubic units	PRECISION 95% PROB. ±%
1	1						
	2						
	3						
	etc.						
	Total						
2	1						
	2						
	3						
	etc.						
	Total						
etc.	1						
	2						
	3						
	etc.						
	Total						
Total (inventoried area)							

1/ Volume to be defined in a footnote

2/ See footnote 3/ Table VI-2

Table VI-6

Volume 1/ According to Use Classes and Species or Species Groups by Inventory Classes 2/

Administrative unit or other specific classes:

Date of inventory ....

Species or Species Groups by		Inventory Classes								
Use Class 3/	Name of Species	1 (area = ...) Per area unit	Total	2 (area = ...) Per area unit	Total	3 (area = ...) Per area unit	Total	etc. (area = ...) Per area unit	Total	Total
				(Volume in cubic units) 1/						
1	1									
	2									
	3									
	4									
	etc.									
2	1									
	2									
	3									
	4									
	etc.									
etc.	1									
	2									
	3									
	4									
	etc.									

1/ Volume to be defined in footnote.

2/ See footnote 3/, Table VI-2

3/ Example of "Use Classes": 1: Presently marketable species
2: Species not yet marketable but of potential value
3: Species of no present value and of unknown potential value

Each species will occur in only one of the three use classes. These classes may be further sub-divided according to local need.

Table VI-7

Stock Tables for Each Administrative Unit and Inventory Class 1/ According to Dbh Classes

Administrative Unit (or other specific class): .... **Date of Inventory:**

Inventory Class: .... **Area in hectares:** ....

SPECIES OR SPECIES GROUPS	D.B.H. CLASS CM. 2/							
	Volumes		Volumes		Volumes		Volumes	
	Per area unit	Total	Per area unit	Total	Per area unit	Total	Per area unit	Total
1								
2								
3								
4								
5								
6								
.								
.								
.								
.								
.								
.								
.								
.								
.								
TOTAL								

1/ See footnote 3/, Table VI-2

2/ Class limits should be shown for each dbh class in agreement with limits indicated in table of paragraph 242.1 in Chapter V.

Table VI-8

Net Annual Volume Increments 1/ for Inventory Classes 2/ by Administrative Units

Inventory Class	Administrative Units						Total volumes all units
	1		2		etc.		
	volumes		volumes		volumes		
	Per ha area unit	Total	Per ha area unit	Total	Per ha area unit	Total	
1.							
2.							
3.							
4.							
5.							
6.							
etc.							
All inventory classes							

1/ (a) Specify how volume increment figures have been obtained and whether they are:

for all forests considered as productive; or

for forests presently under exploitation.

(b) State whether all species are included (non-commercial, etc.)

If no, which species are included and what percentage of total volume do the species included represent.

(c) Specify if all ages and diameters are included; if no, which ages and/or diameters are included.

2/ See footnote 3/, Table VI-2

314.2 Significance and accuracy

The final tables should contain some indication of the reliability of the results. Besides the standard errors which should be given for every level of stratification for which final result tables are computed, careful consideration should be given to the significance of the results. If, for example, on a certain level of stratification the number of sampling units representing a particular stratum is too small, the corresponding result tables for this stratum should be omitted. If for some reason, however, it is deemed useful to produce these results, their relative reliability should always be indicated by giving the area of the corresponding sample and the number of sampling units. The mention of such indications is therefore highly recommended.

The accuracy with which the different results are given depends on the total error of these results (including sampling and measurement errors). Accuracy of the results should be of the same order of magnitude as the estimated total error.

The accuracy of frequency figures - numbers of trees per area unit of given species or species group and of given diameter classes - must be compatible with their expected total error: a very small number of trees/ha has often a high total error and consequently has only an indicative value. A sensible disposition would be to indicate the figure by a special sign instead of presenting it in the same way as the other figures. A similar presentation to that indicated by Guinaudeau (1973) could be applied:

blank	(no figure)	:	no data in the stratum cell concerned
dash	(-)	:	no trees for the stratum cell concerned
asterisk	(*)	:	at least one tree within the stratum cell, the average number of trees/ha however being less than a given figure (say 0.1/ha)
figure		:	the number of trees/ha of the stratum cell with an accuracy of 0.1 tree /ha

If it is intended also to produce the very small values, it is better to present a stand table with the actual numbers of trees found in the sample by species or groups of species and by diameter classes.

Presentation of inventory results with an accuracy much higher than their expected total errors is illusive and misleading, the more so when they are obtained by EDP, since people trust EDP more than manual data processing.

Emphasis must also be placed on consistency in accuracy of the results: if, for instance, the mean volume per ha is given with an accuracy of 0.1 m^3 and the total area of a block with an accuracy of 100 ha, the total volume should not be given to the nearest cubic metre.

315 System design. A system design for data processing as a whole should indicate the logical sequence of the various "activities" to be considered in the planning and implementation phases. Figure VI-1 illustrates this in flow-chart form in the case of processing of field intentory data including sample tree measurements for assessment of volume equations, the area data being derived separately by photo interpretation.

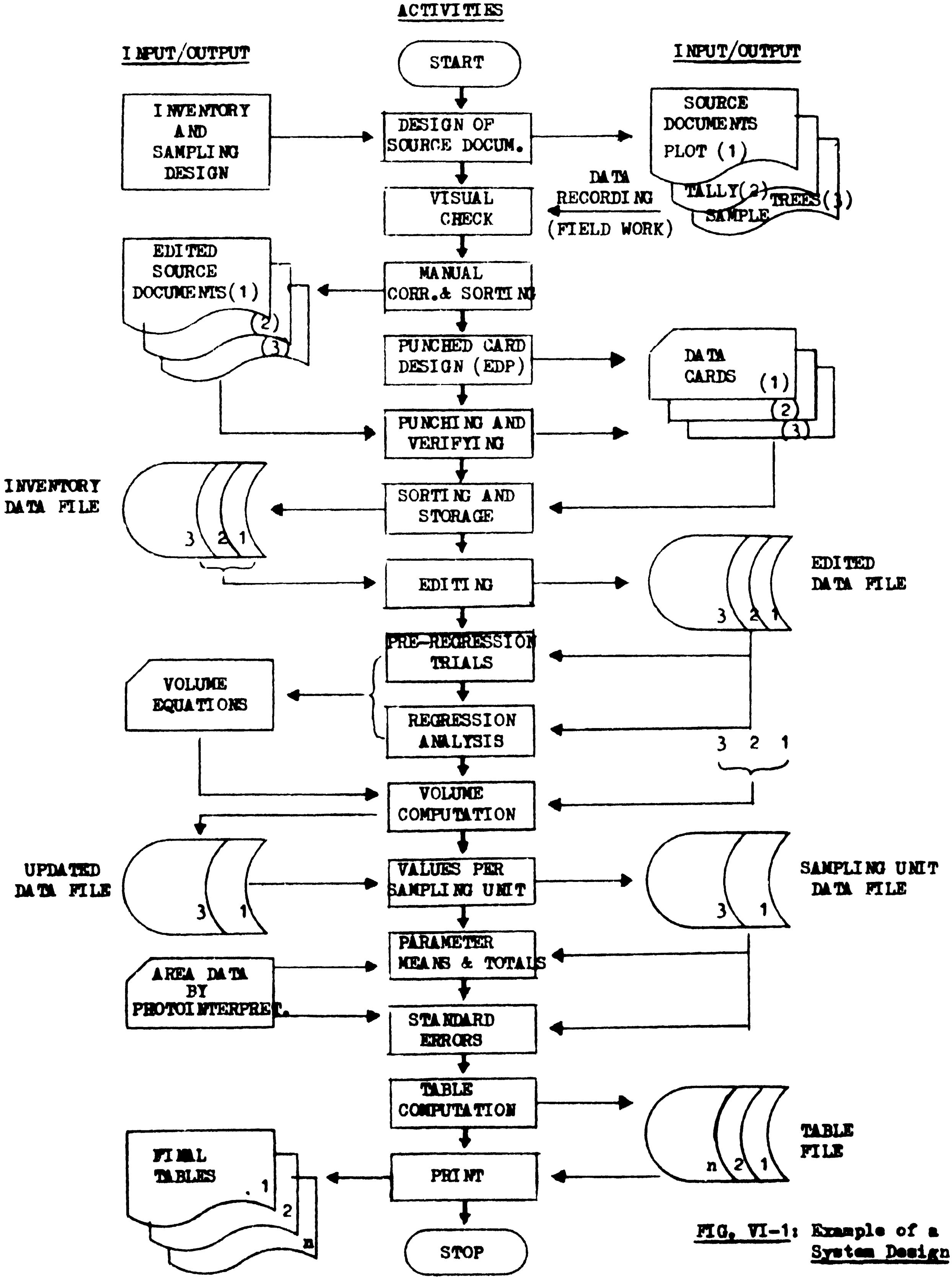


FIG. VI-1: Example of a System Design

A system design is useful for the following reasons:

(a) The different steps foreseen in a provisional checklist are placed in logical order;

(b) the system design clarifies the way the results are produced, from the basic data by the computational procedures corresponding to the inventory design;

(c) the system design is essential to decide upon the <u>type of data processing</u> to be employed;

(d) the system design is a necessary tool for all time and cost estimates related to data processing;

(e) in the case of EDP, the system design is an essential source of information for the analyst/programmer to develop the appropriate computer routines; the system design is finally of great help in deciding whether the data processing is to be carried out by the inventory project itself or whether it must be subcontracted to specialised data processing firms (see details in paragraph 332).

32 <u>Selection of type of data processing</u>

321 <u>Manual data processing</u>. There are a number of circumstances under which manual processing by means of mechanical or non-programmable electronic desk calculators may be considered the most appropriate way of processing inventory data. When deciding upon the type of data processing to be used the factors to be considered are:

- the amount and complexity of data (input)
- scope of the inventory
- the time and cost factors
- available expertise and machine capacity for more sophisticated processing procedures, such as EDP.

For small-scale inventories, especially in relatively simple forest conditions (e.g. few species and little variation in forest types), manual data processing may be more appropriate than EDP since the latter requires greater initial investment and investigation prior to the actual processing. In addition, manual processing may be more generally preferable when a relatively small amount of data are to be treated and results are required fairly rapidly. Manual processing cannot of course be avoided, even in large-scale inventories, if no computers or competent staff are available for EDP.

If, on the other hand, EDP is adopted, manual processing serves as a procedure for determining the various computing steps and to analyse the computing procedure to be used as a basis for the EDP programming. Furthermore, manual calculations are essential for testing EDP. This is particularly relevant when EDP is being subcontracted to outside institutions or firms. The programmes are checked by calculating a small portion of the required results manually and by comparing the results obtained with those of the computer using a set of test cards. This is often the only means of detecting errors in the programmes.

To avoid human error as much as possible when manually processing data, it is essential to give clear instructions for all calculations, for instance by means of detailed system designs. In addition it is of great help if all computations are done on special <u>predesigned forms</u>, in which all steps of computation are described and the user has to follow the instructions given on the form. Such forms have been developed by Dawkins (1968) at the Commonwealth Forestry Institute, Oxford, for the calculation in classical statistical designs including basic sampling designs (unrestricted random and stratified random). Analogous forms can be designed for any type of manual processing for forest inventory.

322 Electronic data processing (EDP). EDP by means of digital computers requires from the inventory expert a basic knowledge of the fundamental concepts of a computer, its advantages and restrictions (for details see Loetsch, Zöhrer and Haller 1973, and cited literature). The basic elements of EDP as compared with those of manual data processing are:

Items	Manual Processing	EDP
1. Instructions for computation	basic mathematical computation rules	programmes in problem-oriented languages (e.g. FORTRAN, ALGOL, COBOL, PL1)
2. Data to be treated	handwritten or typed data on field recording documents	data input in machine-readable form (e.g. punched cards)
3. Computation	by man	by control unit, also called Central Processing Unit (CPU)
4. Auxiliary devices	desk calculators, slide-rules, calculation tables (e.g. trigonometry or logarithm tables)	arithmetic and logic unit within the computer
5. Intermediate results	calculation and composition of tables etc.	automatic storage by storage facility in the CPU (computer memory) or on tapes/disks/drums during operation
6. Results	written or typed result tables, etc.	automatically printed results (print-out sheets)

The advantages of EDP compared with manual processing are evident:

- manpower is only necessary during the phase of setting the rules for computing (i.e. the programming phase). Once the programmes have been developed and tested by the analyst/programmers in close collaboration with the inventory expert, the computer carries out all calculations automatically, so that human error is avoided;
- arithmetic and logic operations which are carried out in manual processing by man or auxiliary devices, are preprogrammed and operational during one "run" 1/ in the computer;
- tables and intermediate results (e.g. volume, stand or stock tables) can be stored in the CPU and every "cell" 2/ can be addressed automatically at any and every moment during the processing operations;
- all results can be printed in definitive form to be included directly in the final report.

1/ "Run" or "job" signifies the whole operation carried out by the computer under the command of one programme or one set of programmes between the start and stop signal of the system control.

2/ A "cell" is the smallest unit in the computer which can be addressed and occupied directly by the programme command.

However, the disadvantages of EDP are as follows:

- specialists are required for writing the programmes (analyst/programmers) and for running the machine (operators);
- the inventory project must have access to a suitable computer centre;
- the basic data has to be transferred to machine readable documents prior to processing, the transfer being one of the main cost components of EDP.

It is evident then that data processing for a given inventory has to be evaluated carefully before deciding whether EDP or manual processing is the appropriate method. However, in most forest inventories a huge amount of data (e.g. 50,000 - 100,000 logical records) has to be treated and various types of output (result tables) are required. Therefore, in most cases, EDP will be chosen, since it allows, after having captured the data in machine-readable form and prepared the programmes, for the processing of the complete results very quickly in their final form. In addition, results can be reprocessed very easily and at a small additional expense if some changes are required in the computation. This is the case, for instance, when a new breakdown of areas by inventory units is necessary or when a new grouping of species or a new set of volume specifications is adopted.

The basic data stored by EDP on tapes, disks or drums can be considered as a <u>data bank</u>. Whenever additional information on the inventoried area or parts of it are required they can be processed using the data bank as input. The facility of data storage is of particular importance in continuous forest inventory (CFI) for updating purposes or for timber forecasts made from data recorded at different periods. Finally, data banks are also useful for the elaboration of countrywide or region-wide statistics using the basic data of various forest inventories.

If electronic processing of the data of a forest inventory is to be used, it must be decided at an early stage during the planning of the inventory. The following steps have to be taken into consideration by the inventory expert:

(a) <u>During preparatory phase</u>

1. Definition of the final results to be reached by the inventory in relation to its objectives.
2. Listing of the basic parameters to be recorded either in the field or from other sources (e.g. aerial photographs and maps).
3. Elaboration of the system design (see paragraph 315).
4. Survey of the available computer facilities with the aim of selecting those which can cope with a part or the whole of the processing work.
5. Design of recording documents and punched cards (or other machine-readable documents).
6. Development of flow charts for the input and editing programmes by the analyst/programmer according to inventory and system designs in close collaboration with the inventory specialist.

(b) <u>During the implementation</u>

7. Elaboration and testing of the input and editing programmes by the analyst/programmer.
8. Punching of basic data and editing of the data.
9. Correction of incorrect data in close collaboration with the field crew leaders and continuous storage of correct data on tapes,disks or drums.
10. Flow charts for calculation and output programmes, and for programming and testing according to the inventory and system design.
11. Documentation of the data processing system.

(c) After completion of data collection

12. Production of final results (output).

13. Storage of basic data and intermediate results (data bank) on tapes.

The main workload for the inventory specialist in relation to EDP occurs before and during the first part of the implementation stage of the inventory. Data processing has to be carefully analysed from the very beginning of the inventory operation and must be taken into account in the related cost and time studies.

323 Combined types of data processing. In certain cases (small inventories, working plans, etc.) manual and electronical data processing may be combined. While editing and minor calculations are carried out manually, more complicated procedures such as regression analysis or sampling error calculations are performed on pre-programmed desk computers (such as the WANG 700 series or Olivetti 600 series) or larger digital computers at computer centres. One disadvantage of this method is that editing is not carried out automatically, but the main drawback comes perhaps from the fact that the data are manipulated and transferred several times which may result in additional errors during processing. Combined methods of data processing are thus different from totally integrated data processing procedures which can be seen as "closed systems", and in which the basic data remain untouched, once they have been edited. Therefore, they should be recommended only if EDP is not feasible.

33 Some practical aspects of EDP

331 Project-integrated data processing. From the practical point of view it is important to decide which parts of EDP will be carried out in the project. As mentioned above, the system design has to be prepared in any case by the inventory expert himself. Punching of data could be done in the project, if a punching machine could be hired for a determined period and secretarial/clerical staff could be trained in the use of card punchers and verifiers. Programming could be incorporated in the project, if the inventory expert has experience and time for this activity, or if other staff members could be trained in computer programming. Since programming in FORTRAN or any other problem-oriented computer language can be learnt easily within a two or three week programmer's course, the field crew leaders may, for instance, carry out the programming during periods when not engaged in field work. This method has been practised with success in the Swedish National Forest Inventory for many years.

Totally project-integrated data processing has the advantage of having continuously close contact between the inventory staff and the data processing staff, which is of particular importance during the implementation phase (editing of basic data) and later stages, such as pre-regression studies for volume estimation. As for punching, experience has shown that these activities in many cases can be carried out more cheaply and effectively outside the project at specialised firms, which normally have qualified staff and long experience at their disposal, which reduce punching errors to a considerable extent.

332 Sub-contracted data processing. Those parts of data processing not being carried out by the project itself will normally be sub-contracted to adequately staffed computer centres, data processing consulting firms, or data processing departments of universities, etc. A few forms of sub-contracts merit consideration, the most appropriate to be chosen according to the special needs of the inventory project.

332.1 Sub-contracting data processing as a whole

All data processing will be subcontracted, including card punching, the elaboration of the system design (in close collaboration with the inventory expert), the treatment of the data on computers following the agreed system design and the preparation of the final results required by the inventory project.

A totally sub-contracted EDP system requires from the inventory project a very careful appraisal and statement of the work to be done under the contract, defined as follows:

I. The technical specifications.

(a) Definition of the computational procedures, such as:

- regression models for volume equations or taper functions;
- significance tests;
- quality assessment (calculation of different types of volumes);
- sampling error calculation on the different levels of study.

(b) Specifications of the output required, such as:

- stand and stock tables for
  - species
  - groups of species
  - forest types
  - inventory units

  containing figures per area unit and/or totals;
- volume tables (tabulation of the volume equations used for volume estimation);
- plotted scatter diagrams, including the calculated regression line;
- histogrammes of diameter distribution for main species or species groups, forest types, logging units, etc.;
- breakdown of total inventoried area by classes of accessibility, preferably for blocks or smaller units.

II. Obligations of the contractor

- Timing of the EDP work;
- delivery of provisional results for checking and final approval by the project;
- documentation of the EDP programmes, including flow charts of computation procedures, programme lists, programme decks on cards and/or magnetic tapes, detailed description of programme operation (preparation of system control cards, parameter cards, etc.);
- delivery of corrected and sorted data tapes for storage purposes and future use by the project;
- delivery of monthly progress reports on status of work done and planned for the forthcoming month.

III. Cost breakdown into:

- man hours, unit costs and total costs for:
  - supervisory time
  - analyst/programmer:
    - programming/testing
    - documentation
    - production
  - key punching/verifying
- computer time (hours and unit costs, description of computer model, type, series):
  - testing
  - production
- miscellaneous:
  - rent or purchase of tapes
  - travel costs of the contractor
  - expenditure costs, etc.

332.2 Sub-contracting parts of the data processing

Many forms of sub-contracting parts of the data processing are feasible, such as:

- project-integrated punching and verification of the data, editing on small computers, to which the project might have access; sub-contracting of data generation and production of final results to large computer centres;
- the use of the computer and other installations of a computer centre only.

When data processing totally integrated within the inventory project is not possible, partly sub-contracted EDP is in many cases the most appropriate alternative. Technical and other specifications to be defined in the contract will be less detailed. If the contract between the inventory project and the contractor concerns only the use of a computer and related facilities, the following specifications should be clearly stated:

- use of the computer itself (reservation of computer time, staffing of the computer with operators);
- use of peripheral hardware (card-puncher, sorter, doubler and translator);
- use of computer hardware (tapes, discs, drum files for predetermined periods);
- use of computer software (statistical routines, etc. - see paragraph 233 of Chapter VI);
- system and programming advice from the computer centre in system-oriented questions of the computer language and the system control.

In most cases the computer centre should charge only for the use of the computer itself and perhaps access to the computer software, on a time or per-case basis, respectively. Other services should be granted free of charge. These points should be fully agreed upon whenever an inventory project contracts EDP work to a computer centre. Only in very few cases will the use of the computer be totally free to the project.

233 Some views of the use of standard programmes. To our knowledge there have not yet been developed generalised EDP systems for forest inventory applicable to various types of inventory (sampling) designs and flexible enough for producing different types of result tables. The FINSYS system developed in the United States several years ago (see Frayer et al 1968), although highly flexible, covers only a few sampling designs used in that country and requires fairly large computers (minimum 32-K memory). In addition, the programme control by parameter cards appears to be particularly sophisticated.

FAO is therefore at present developing a generalized EDP system for tropical forest inventory with the following main features:

- full flexibility for the INPUT and EDITING parts;
- restrictions of the generation and error calculation phase to the most common sampling designs;
- certain flexibility in the production of OUTPUT (result tables), to generate tables in addition to the standard ones recommended by FAO (see paragraph 314.1).

There are, however, quite a few other pre-programmed EDP routines available at almost all computer centres which are very useful and can be included in forest inventory EDP systems. All regression analysis, variance and co-variance trials, scatter diagrams and histograms, stratifications and functional descriptions of distribution can be calculated by means of standard programmes, provided that the computational procedures incorporated in the programmes are appropriate to the problems to be solved. Collections of standard programmes to be recommended are, for instance:

- BMD (Biomedical computer programmes), developed at the University of California (see Dixon 1968), originally for IBM 7094 computers but applicable to other computer makes with a minimum of approximately 32 K-words memory.

- Statistical programmes of the German Calculation Centre (DRZ = Deutsches Rechen-Zentrum - see DRZ 1969), which are designed to complement the BMD series.

In addition, almost all computer manufacturers supply their computer centres with pre-programmed statistical routines, to which the user can have direct access, since these "STATPACKS" are normally stored on disks or drums.

Standard programmes should be used whenever possible during forest inventory data processing operations, since time and a considerable amount of money can be saved.

CHAPTER VII

CONSIDERATIONS ON INVENTORY DESIGNS

CHAPTER VII

CONSIDERATIONS ON INVENTORY DESIGNS

1 Introduction

The former chapters have been devoted to the study of the principal techniques that are useful in forest inventory, namely sampling techniques, remote sensing techniques, forest mensuration techniques and data processing. Planning and designing a forest inventory consist mainly in developing the most efficient combination of these various techniques to fulfil the objectives of the operation, taking into account the prevailing human and environmental conditions. In this respect even data processing problems have to be contemplated from the very beginning since available means in manpower and computing facilities also have a bearing on the type of inventory methodology used, as has already been mentioned in chapter VI.

There is no point trying to cover all the situations and objectives assigned to forest resource surveys and the corresponding combinations of techniques which are likely to be the most appropriate in each case. This would be an endless and illusory task. A more modest and also more realistic approach is used in this chapter where some problems arising from the combination of these techniques will be dealt with and some recommendations will be made on the suitability of these techniques to actual working conditions.

Techniques of volume estimation and quality assessment have already been compared in chapter V. Their effects on the precision and on the usefulness of the inventory results are far from negligible; but, especially in mixed tropical forests, the largest part of the total cost involved comes from the field enumeration work. The most important questions to be considered are therefore related to the latter part of the inventory work and are mainly the following:

- to what extent interpretation of remote sensing imagery can be combined with the field enumeration work so as to decrease the effort spent on the latter, and thus reduce the total cost of the inventory (for a given precision of the final estimates of the parameters over the whole inventoried area) ?

- the importance of interpretation of remote sensing imagery being decided upon, what are the most suitable characteristics of the field sampling design ?

Some indications useful in solving these problems are given in the two main following sections of this chapter. The formulas corresponding to some classical combinations of photointerpretation and field sampling procedures are indicated, together with the cases to which they apply (section 2). General formulas corresponding to the most classical field sampling designs have already been given in chapter III and the contents of section 3 are restricted to some guidelines on the selection of the most appropriate field sampling design with special reference to mixed tropical forests.

Most forest inventories aim at estimating the characteristics of forest stands at a given time. There exist, however, some permanent inventory designs which consist in the combination of different samples selected on successive occasions, which can be grouped under the generic denomination of "Continuous Forest Inventory", and which are briefly commented on in section 4. Another type of sampling designs follows a stepwise procedure, in which the decision whether or not to undertake further sampling depends on the results already obtained from the sample; this is called sequential sampling and is dealt with in section 5.

2 Combinations of photointerpretation and field sampling procedures

21 Preliminary remarks

It is assumed in this section that some basic conditions which are those already indicated in the introduction of Chapter IV are fulfilled: the total area of the inventoried zone is supposed to be exactly known and mapped at a suitable scale (which allows for the definition of frames for sampling designs), and the stand characteristics are estimated through field sampling (the case of photogrammetric measurements of stand characteristics being excluded as it is generally not applicable to inventories of mixed tropical forests).

The main use of interpretation of remote sensing imagery in forest inventory is to stratify the area to be inventoried into more homogeneous parts or strata which are sampled separately in the field, in order to get more precise estimates of the total values of the forest characteristics over the whole area. For reasons mentioned in the following paragraph it is relatively rare that areas of the strata are known exactly or almost exactly, and generally they have to be estimated through a sound sampling design.

22 Areas of the strata exactly or almost exactly known

Stratum areas can be said to be exactly or almost exactly known when the actual and present limits of the strata are drawn on a reliable and stable planimetric map and their areas carefully planimetered or estimated very precisely by use of very dense dot grids (see section 5 of chapter IV). The actual and present limits of the strata can be located on the photographs if:

- very recent aerial photographs at a suitable scale are available, or, if they are not very recent (say if they are two or three years old, but not more) if no significant changes are likely to have occurred between the date of the aerial coverage and the date of the field inventory (significant, that is, in relation to the accepted accuracy of the area figures);

- no systematic photointerpretation error is expected, and consequently none - or a negligible part - of the sampling units of the field inventory will have to be transferred from the strata to which, through misinterpretation, they have been assigned by photointerpretation to different strata to which they actually belong.

It can be easily understood from the above considerations that such cases very seldom happen. Even if the aerial coverage has been taken in the same year as the field work, inconsistencies and errors in the photointerinterpretation work can always be expected since conventional interpretation of remote sensing imagery is not a purely objective exercise. Inconsistencies and errors over time by the same interpreter or between interpreters can be avoided only if the stratification is simple and easy and if there are sharp limits between strata (as has already been mentioned in paragraph 334.1 of chapter IV it is generally difficult to draw objectively a limit between strata as there may be more or less wide transition zones).

In the rare cases when an exact (or almost exact) evaluation of the areas of the strata can be secured, i.e. when it is assumed that there is no misinterpretation in the photointerpretation, the sampling frame for each stratum is well defined and an independent selection of the field sample can be made within each stratum. The mean values and estimated variances of the forest characteristics per ultimate unit over the whole population estimated from the field sample can be derived from the corresponding formulas given in chapter III for sampling designs with stratification prior to sampling (formulas 5, 6 or 11, 12 in case of one-stage sampling designs), in which the total sizes N_h (or X_h) of the strata and N (or X) of the whole population can be replaced by the total areas S_h and S respectively.

The total values of the forest characteristics for the whole inventoried area is obtained by multiplying the mean value per ultimate unit by the total number (which is exactly known) of ultimate units in the whole area. The percentage standard error is the same as that of the mean value.

It may happen that an unstratified sample is first selected for the whole area and that stratification is made by photointerpretation after the sampling on the basis of criteria recognized in the field and identifiable on the photographs. If it is possible to assume that this stratification is fully valid, then the exact sizes of these strata can be known and the estimated means and their estimated variances are derived from formulas (7) and (8) of chapter III (in the case of one-stage sampling with equal units), which are somewhat different from those corresponding to stratification prior to sampling. Total values are obtained in the same way as in the case of stratification prior to sampling and the estimated relative standard errors are the same as for the corresponding mean values.

23 Areas of the strata estimated through sampling

In this case the estimation of the strata through a sampling design increases the sampling error of the estimates of the total values of stand characteristics over the whole inventoried area or over individual strata.

In forest inventory there are various ways of estimating the areas of the strata using sampling. The main alternatives are:

(a) sampling on the photographs (or on the maps), the photointerpretation being supposed to be unbiased (same case as in the above paragraph, planimetering being replaced by sampling);

(b) sampling in the field from the same (or a larger) sample used for the estimation of the stand characteristics: in this method the area estimates are supposed to be unbiased and do not need to be corrected since identification of the strata is made on the spot;

(c) sampling from the photographs (or even possibly planimetering on the maps), the area estimates obtained being afterwards corrected through a sampling in the field, using the sample used for estimation of the stand characteristics or a larger sample.

When estimating areas through sampling it is important also to distinguish the case when the sampling units are points or plots (the associated parameter having the values 1 or 0 according to whether the plot belongs to the relevant stratum or not) from the case when the sampling units are lines or strips (in which case the associated parameter is a length or a ratio of lengths, both continuous variates).

231 Area estimates from one sample only.[1] Stratification and estimation of the areas of the strata can be made by sampling on photographs or in the field, if photographs are considered unsuitable (too old or too bad to allow for a useful stratification). The sample used for estimation of the areas of the strata may be the same as the one used in the field for estimation of the stand characteristics or may be a larger one (including the sampling units used for the estimation of the stand characteristics).

(1) Sample is used here as in the rest of this manual to designate the whole set of sampling units selected according to a given sampling design.

231.1 Area estimation using plots as sampling units

In this case the associated parameter can take the values 1 or 0 according to whether the plot belongs to the particular stratum considered or not. The area of a stratum is obtained by multiplying the total area of the inventoried zone (which is supposed to be known exactly) by the proportion (estimate) of plots falling in this stratum.

231.11 Area and stand characteristics estimation from the same sample

If area estimation is made by photointerpretation, the sampling units in the field used for the estimation of the stand characteristics are centred on the plots interpreted on the photographs (see paragraph 334.2 of chapter IV). They may be single plots or clusters of plots, a bit smaller or larger than the photoplots but each of them is supposed to belong entirely to the stratum of the corresponding plot on the photographs (no correction of the photointerpretation is supposed to be necessary).

If the plots are randomly distributed the proportions P_h of the strata and their variances are estimated by formulas (3) and (4) of chapter III if it is a one-stage sampling design, or by formulas (13')and 14')of the same chapter if a two-stage design has been used, in which the primary units are the effective areas of the photographs (supposed equal) and are selected at random, the same number of plots (secondary units) being sampled on each selected photograph. Other sampling designs can be contemplated as has already been mentioned in paragraph 532 of chapter IV. The percentage standard errors of the estimates of the areas of the strata are equal to those of the corresponding proportions since the total area is supposed to be known exactly.

If the plots are systematically distributed in a one-stage design, it is recommended to use the formula given in paragraph 531 of chapter IV for the estimation of the variances, in which the constant k is given a value according to the shape of the corresponding stratum.

The estimates of the mean values per ultimate sampling unit of the stand characteristics and their variances are obtained by the formulas of the corresponding unstratified sampling design. The corresponding estimates of the total values over the whole population are obtained by multiplying the estimated means by the total number of plots in the whole inventoried zone (or by its total area if they are means per area unit) and their percentage standard errors are the same as those of the respective means.

Estimates of the means per ultimate unit in each stratum and of their variances are obtained from the individual values in the sampling units belonging to the corresponding stratum. However care must be exercised since the sampling is done within the population as a whole and the same formulas as for the whole population do not apply necessarily to each stratum. Estimates of the totals per stratum are obtained by multiplying the corresponding estimated means by the estimated area of the respective stratum.

If $\bar{y}_h$ is the estimated mean per area unit of a stand characteristic y in stratum h,

$\hat{P}_h$ is the estimated proportion of stratum h

S is the total area of the inventoried zone,

an estimate $\hat{Y}_h$ of the total value of this characteristic in stratum h is: $\hat{Y}_h = S\hat{P}_h\bar{y}_h$

and an estimate of its variance is:

$$v(\hat{Y}_h) = S^2 \left[\hat{P}_h^{\,2}\, v(\bar{y}_h) + \bar{y}_h^{\,2}\, v(\hat{P}_h)\right]$$

where $v(\bar{y}_h)$ and $v(\hat{P}_h)$ stand respectively for the estimated variances of $\bar{y}_h$ and $\hat{P}_h$. This formula is acceptable if $v(\bar{y}_h)$ and $v(\hat{P}_h)$ are small relative to $\bar{y}_h^{\,2}$ and $\hat{P}_h^{\,2}$ respectively.

Attention is drawn to the fact that these designs are definitely different from designs using stratification after sampling. In these latter it is assumed that the sizes of the strata are known exactly or almost exactly, which is not the case with the designs studied in this paragraph where only an estimate of the sizes of the strata is obtained.

In the above paragraphs, as well as in the rest of section 23, we do not consider the case of correction or weighting of the values found in the individual plots interpreted on the photographs which are necessary for taking into account the variation in scale and in overlaps of the photographic coverage used (see paragraph 334.2 of chapter IV). This correction corresponds to coefficients which appear in the formulas of the estimated means and totals and adds some complication to the estimation of the corresponding variances. In order to avoid it, it is recommended that the sample to be used for area estimation by photointerpretation is laid out on an existing map or on the corresponding uncontrolled mosaic provided this can be accepted as a reasonable approximation to a map. In case correction is deemed preferable, the reader will study with profit the examples given in paragraph 25.32 of "Forest Inventory" (Volume 1, pages 235-244) by F. Loetsch and K. Haller.

231.12 <u>Area estimation from a larger sample than the field sample used for estimation of stand characteristics</u>

The field sample for the estimation of the stand characteristics is a <u>subsample</u> of the sample used in photointerpretation or in the field for the estimation of the areas of the strata. If area estimation is made by photointerpretation the field sampling units of the subsample are centred on the plots interpreted on the photographs and each of them is supposed to belong entirely to the stratum of the corresponding plot. We will assume that the selection of the large sample and of the subsample from the large sample are both random one-stage samples. This type of combined sampling is called two-phase sampling or <u>double sampling</u>.

<u>Areas</u> are estimated <u>from the large sample of plots</u>, in the same way as described in the preceding paragraph.

If $\hat{S}_h$, $\hat{P}_h$ and S stand respectively for the estimated area of the stratum h (L strata in total), the estimated proportion from the large sample and the total area (exactly known) of the whole inventoried zone, we have:

$$\hat{S}_h = \hat{P}_h . S \qquad \left(\sum_{h=1}^{L} \hat{P}_h = 1\right) \qquad (1)$$

The estimated <u>means</u> $\bar{y}_{st}$ of the stand characteristics over the whole inventoried zone per sampling unit are given by:

$$\bar{y}_{st} = \sum_{h=1}^{L} \hat{P}_h \bar{y}_h \qquad (2)$$

where the $\bar{y}_h$ are the estimated mean of the stand characteristic per sampling unit in each stratum obtained from the field subsample, the summation being extended to all the strata.

The calculation of the variances of the estimates $\bar{y}_{st}$ depends on the way the subsample has been selected from the sample.

(a) If the numbers of sampling units per stratum in the subsample n_h do not depend on the estimated proportion $\hat{P}_h$ of the corresponding stratum, then an estimate of the variance of $\bar{y}_{st}$ is:

$$v(\bar{y}_{st}) = \sum_{h=1}^{L} \left[\left(\hat{P}_h^{\,2} - \frac{\hat{P}_h}{n'}\right) \frac{s_h^2}{n_h} + \frac{\hat{P}_h(\bar{y}_h - \bar{y}_{st})^2}{n'} \right] \qquad (3)$$

which can also be written as:

$$v(\bar{y}_{st}) = \sum_{h=1}^{L} \left(\hat{P}_h^{\,2} - \frac{\hat{P}_h}{n'}\right) \frac{s_h^2}{n_h} + \frac{1}{n'} \left[\sum_h \hat{P}_h \bar{y}_h^{\,2} - \left(\sum_h \hat{P}_h \bar{y}_h\right)^2 \right] \qquad (3')$$

where: n' is the number of sampling units of the large sample

s_h^2 is the estimated variance of the stand characteristic y in stratum h:

$$s_h^2 = \frac{\sum_{i=1}^{n_h} (y_{hi} - \bar{y}_h)^2}{n_h - 1}$$

(i being the index of a sampling unit in stratum h of the field subsample)

(b) If the n_h depend on the $\hat{P}_h$, the formula giving the estimated variance of $\bar{y}_{st}$ is somewhat different. In case of a proportional allocation of the sampling units in the field subsample, i.e. if $n_h = n\hat{P}_h$ where $n = \sum_{h=1}^{L} n_h$ is the size of the subsample, an estimate of the variance is:

$$v(\bar{y}_{st}) = \sum_{h=1}^{L} \hat{P}_h \cdot \frac{s_h^2}{n_h} + \frac{1}{n'} \left[\sum_{h=1}^{L} \hat{P}_h \bar{y}_h^{\,2} - \left(\sum_h \hat{P}_h \bar{y}_h\right)^2 \right] \qquad (4)$$

Formulas (2), (3), (3') and (4) are known as formulas of double sampling with stratification. Totals over the whole inventoried area are obtained by multiplying the estimated means by the total area exactly known and their relative standard error is the same as those of the corresponding means. Estimates of the totals per strata are:

$$\hat{Y}_h = \hat{S}_h \cdot \bar{y}_h = (\hat{P}_h \cdot S)\bar{y}_h \qquad (5)$$

231.2 Area estimation using parallel lines as sampling units

In this case the line will be considered as the sampling unit and the associated parameter for a given stratum is a continuous variable since the length of the portion of a line which is found (on the photographs or maps or possibly in the field) within a given stratum can take in principle all values between 0 and the total length of the line . The case applies also to strips and to lines of plots, the occurrence of the stratum being checked only at the plots in the latter case, and even also to clusters of plots, provided that the number of plots per line or per cluster is large enough.

We will confine ourselves to the cases when the same sample is used for estimating the areas of the strata and the stand characteristics.

If all the lines have the <u>same total length</u> l within the whole inventoried zone (e.g. if the inventoried zone is square or rectangular and the lines parallel to one side of the area) the <u>areas</u> of the strata are estimated (in a one-stage design) by:

$$\hat{S}_h = S . \frac{\sum_i l_{hi}}{nl} = \frac{S}{l} . \bar{l}_h \qquad (6)$$

where S is the total area of the inventoried zone

$\bar{l}_h$ is the estimated mean length of a line (sampling unit) in the stratum h: $\bar{l}_h = \frac{\sum_i l_{hi}}{n}$ (i being the index of a line)

If the parallel lines are randomly distributed formula (2) of chapter III is applicable to the estimation of the variance of $\bar{l}_h$, the percentage standard error of $\hat{S}_h$ being equal to that of $\bar{l}_h$. If they are systematically distributed formulas suggested in section 423 of chapter III have to be adapted.

In most cases the lines have <u>unequal total lengths</u> and then ratio estimation is necessary. If we assume a one-stage random design of n parallel lines, and if l_i and l_{ih} stand respectively for the total length of line i and the length of the portion(s) of line i within stratum h, an estimate of the area of stratum h will be:

$$\hat{S}_h = S \frac{\sum_{i=1}^{n} l_{ih}}{\sum_{i=1}^{n} l_i} = S \frac{\bar{l}_h}{\bar{l}} \qquad (7)$$

$\bar{l}_h$ and $\bar{l}$ being respectively the means per line of lengths within stratum h and of total length.

The standard error of $\hat{S}_h$ can be estimated by using formulas (10) or (10') of chapter III related to the variance of a ratio estimate.

The estimates of the <u>means</u> per area unit of the stand characteristics over the whole population are <u>ratio estimates</u> in the case when the lines have different total lengths, with total length of a line as the auxiliary parameter. Means for each stratum can be estimated also and will be ratio estimates. But, as has already been said in paragraph 231.11, the sampling design must be considered as <u>unstratified</u>, since the exact size of each stratum is not known. Indications given in the above mentioned paragraph concerning the estimation of the means and totals per stratum are valid also in this case.

The case of continuous lines can be extended to the case of continuous strips, of lines of plots and of clusters.

232 <u>Area estimates with correction in the field.</u> In many cases there are unavoidable mistakes and biases in the photointerpretation work due to the interpreters, to the stratification adopted which may be too refined, to the bad characteristics of the photographs and, most often, to changes in vegetation which have occurred between the aerial survey and the field inventory. Estimation of the areas made by photointerpretation need then to be corrected by <u>field checks made in a subsample</u> of the photointerpretation sample.

We will confine ourselves to the design described below which is very much used in forest inventory in temperate zones and which needs to be adapted in an efficient way in mixed tropical forests, which consists of:

(a) selection of an unstratified sample of plots to be interpreted on the photographs for an assessment of the strata h as identified by photointerpretation, e.g. by a systematic grid put on the effective area of each photograph, or by a systematic grid put on a mosaic of these photographs, or by a random selection on a map of points transferred afterwards onto the corresponding photographs, etc.);

(b) selection (in one stage) of a subsample of plots among the interpreted plots, the number of these plots in each stratum h (as interpreted on the photographs) being dependent or independent of the proportion of this stratum (as found by photointerpretation);

(c) identification in the field of the actual strata k to which the plots of the subsample belong and measurements for estimation of the stand characteristics y in these plots.

If $\hat{P}_h$ is the proportion of plots of the large sample found in stratum h by photointerpretation

$\hat{p}_{hk}$ is the proportion of plots of the subsample found to be in stratum h by photointerpretation and in stratum k in the field (whenever $k \neq h$ there is misinterpretation)

an estimate $\hat{p}_k$ of the actual proportion of stratum k in the whole inventoried zone is given by:

$$\hat{p}_k = \sum_{h=1}^{L} \hat{P}_h \cdot \hat{p}_{hk} \tag{8}$$

An estimate $\bar{y}_{st}$ of the mean value per unit (or per area unit) over the whole inventoried zone of the stand characteristic y is given by:

$$\bar{y}_{st} = \sum_{k=1}^{L} \sum_{h=1}^{L} \hat{P}_h \cdot \hat{p}_{hk} \bar{y}_{hk} \tag{9}$$

where $\bar{y}_{hk}$ is the estimate of the mean value per sampling unit (or per area unit) of the stand characteristic y in the part of actual stratum k belonging to the photointerpretation stratum h.

The estimate of the mean value per unit (or per area unit) in stratum k of y is equal to:

$$\bar{y}_k = \frac{\sum_{h=1}^{L} \hat{P}_h \cdot \hat{p}_{hk} \bar{y}_{hk}}{\sum_{h=1}^{L} \hat{P}_h \cdot \hat{p}_{hk}} \tag{10}$$

The estimated totals $\hat{Y}$ over the whole inventoried zone and $\hat{Y}_k$ over the stratum k are obtained by multiplying the expressions in (9) and (10) respective by S and $S(\sum_{h=1}^{L} \hat{P}_h \cdot \hat{p}_{hk})$, ($S$ being the area of the inventoried zone), $\bar{y}_{hk}$ in formulas (9) and (10) being the mean value per area unit.

An estimation of the variance of $\hat{p}_k$ is given by applying the formula of double sampling with stratification to the variable (1,0) indicating whether a plot interpreted in stratum h on the photographs belongs to actual stratum k or not. Transformation of formula (3') gives thus (in case the n_h are independent of the $\hat{P}_h$):

$$v(\hat{p}_k) = \sum_{h=1}^{L} \left(\hat{P}_h^{\,2} - \frac{\hat{P}_h}{n'}\right) \frac{\hat{p}_{hk}(1-\hat{p}_{hk})}{n_h} + \frac{1}{n'} \left[\sum_{h=1}^{L} \hat{P}_h \hat{p}_{hk}^{\,2} - \left(\sum_h \hat{P}_h \hat{p}_{hk}\right)^2 \right] \quad (11)$$

n' and n_h standing as in formula (3) for the size of the large photointerpretation sample and the number of units of the subsample selected in stratum h. In most cases the term $\frac{\hat{P}_h}{n'}$ can be neglected.

If a proportional allocation of the subsample among the photointerpretation strata h is made, (i.e. if $n_h = n\hat{P}_h$, with $n = \sum_h n_h$), then the formula (11) becomes:

$$v(\hat{p}_k) = \sum_{h=1}^{L} \hat{P}_h \frac{\hat{p}_{hk}(1-\hat{p}_{hk})}{n_h} + \frac{1}{n'} \left[\sum_{h=1}^{L} \hat{P}_h \hat{p}_{hk}^{\,2} - \left(\sum_h \hat{P}_h \hat{p}_{hk}\right)^2 \right] \quad (12)$$

Although the estimates of the variances of the means and totals of the stand characteristics per stratum and for the whole inventoried zone are somewhat complicated, such a design is very useful as it permits a reduction of the error by use of photo-interpretation, even when the photographs are not completely recent as is often the case. (Assistance of a statistician will be looked for to determine an estimate of the variances of the means and totals of the stand characteristics.) However it must be realized that if the discrepancies between photointerpretation and ground checks are likely to be large and if the size of the subsample is relatively small, the areas of the strata will be estimated with a very low accuracy.

24 Other uses of double sampling designs

The double sampling designs indicated above are used to improve the precision of the estimates of the stand characteristics through a better estimation of the size (area) of the strata. They are called double sampling methods for stratification.

However, double sampling designs can be used in forest inventory for other purposes. Double sampling for regression is also used in some cases, for instance when photogrammetric measurements of a stand characteristic (e.g. gross volume of all species) are made on a large sample of plots on the photographs and are corrected by regression on the field subsample of these plots. Assuming that each sample is an unstratified random sample, the corrected mean $\bar{y}_{Re}$ per sampling unit is estimated by:

$$\bar{y}_{Re} = \bar{y} + b\,(\bar{x}' - \bar{x}) \quad (13)$$

where: $\bar{y}$ is the estimate of the mean per sampling unit of the characteristic y obtained from the field subsample

$$\bar{y} = \frac{\sum_{i=1}^{n} y_i}{n}$$

$\bar{x}$ is the estimate of the mean per sampling unit of the photogrammetric measurements of this characteristic on the plots of the field subsample

$$\sum_{i=1}^{n} x_i$$

$\bar{x}'$ is the estimate of the mean per sampling unit of the photogrammetric measurements of this characteristic on the plots of the large sample

$$\sum_{i=1}^{n'} x$$

and b is estimated by:

$$b = \frac{\sum_{i=1}^{n}(x_i-\bar{x})(y_i-\bar{y})}{\sum_{i=1}^{n}(x_i-\bar{x})^2}$$

where x_i and y_i stand for the value of x (photogrammetric measurement) and y (characteristic measured in the field) in the plot i of the field subsample.

An estimate of the variance of $\bar{y}_{Re}$ when the size n of the subsample is not too small is:

$$v(\bar{y}_{Re}) = \frac{s^2_{y.x}}{n} + \frac{s^2_y - s^2_{y.x}}{n'} \tag{14}$$

with: n' being the size of the large sample

$$s^2_y = \frac{\sum_{i=1}^{n}(y_i-\bar{y})^2}{n-1}$$

and $$s^2_{y.x} = \frac{1}{n-2}\left[\sum_{i=1}^{n}(y_i-\bar{y})^2 - b^2\sum_{i=1}^{n}(x_i-\bar{x})^2\right]$$

Double sampling for regression can be imagined for the estimation of a stand characteristic y with any other auxiliary variate x estimated from a larger sample on photographs or in the field and which is linearily correlated with y.

Double sampling for regression is also useful with estimates of <u>areas</u> of strata obtained by <u>reconnaissance flights</u> along parallel transects used, for instance, to correct estimates obtained by photointerpretation. However such methods must be used carefully since it is generally difficult to locate precisely on a map a point overflown because of the irregular speed and orientation of the plane.

When the straight line representing the relation between y and the auxiliary parameter x goes through the origin - i.e. when y tends to zero with x - double sampling is used for ratio estimation. In this case the corrected ratio estimate $\bar{y}_R$ will be equal to:

$$\bar{y}_R = \frac{\bar{y}}{\bar{x}}\,\bar{x}' = \hat{R}\bar{x}' \qquad (15)$$

where $\bar{y}$ is the estimate of the mean per sampling unit of the characteristic y obtained from the subsample

$\bar{x}$ is the estimate of the mean per sampling unit of the auxiliary parameter obtained from the field subsample

$$\bar{y} = \frac{\sum_{i=1}^{n} y_i}{n}$$

$\bar{x}'$ is the estimate of the mean per sampling unit of the auxiliary parameter obtained from the large sample

$$\bar{x}' = \frac{\sum_{i=1}^{n'} x_i}{n'}$$

An estimate of the variance of $\bar{y}_R$ - the smaller sample (size n) being a subsample of the larger one (size n') - is equal to:

$$v(\bar{y}_R) = \frac{s_y^2 - 2\hat{R}\,s_{xy} + \hat{R}^2 s_x^2}{n} + \frac{2\hat{R}\,s_{xy} - \hat{R}^2 s_x^2}{n'} \qquad (16)$$

with n, n', $\hat{R}$ and s_y^2 having the same meaning as above and

$$s_x^2 = \frac{\sum_{i=1}^{n}(x_i-\bar{x})^2}{n-1}$$

$$s_{xy} = \frac{\sum_{i=1}^{n}(x_i-\bar{x})(y_i-\bar{y})}{n-1} \quad \text{(estimate of the covariance of x and y)}$$

An example of double sampling with ratio estimation is the one where an estimate of timber volume is performed in a quick way on a field sample (this quick estimate being the auxiliary parameter x) and a more accurate assessment of the volume (y) being made from detailed tree measurements on a subsample.

Double sampling designs are a very powerful tool in forest inventory either for stratification or with the use of an auxiliary parameter (regression or ratio estimation) but leads in many cases to difficult and rather complicated estimation of the variances of the results. In case of double sampling with ratio or regression estimation the relationship between the parameter to be estimated and the auxiliary parameter has to be assessed and the design must be conceived in order to reduce the unavoidable biases of the estimates. Assistance of a statistician proves to be particularly useful in this case.

3 Considerations on field sampling designs

The former section dealt with some aspects of the combination of information obtained from remote sensing imagery and information collected in the field. It is important indeed when designing a forest inventory to reduce the field work as much as possible by making the greatest possible use of interpretation of remote sensing imagery since this involves less manpower, equipment and operating expenses than field work. However, field work cannot be avoided in most forest inventories, especially when stand characteristics including gross and extractable volumes have to be estimated precisely. Even in the case of surveys of homogeneous stands using large-scale aerial photography and photo volume tables, ground checks are necessary to correct, through a double sampling procedure, the estimates obtained from the photographs. In mixed tropical forests field sampling is generally the most important and expensive part of forest inventory operations, due to the limitations of interpretation of aerial photographs in these areas. As has already been mentioned in chapter IV the first constraint on the use of aerial photographs for estimation of stand characteristics in mixed tropical forests is the difficulty of identifying tree species. But even if species could be identified satisfactorily, other difficulties in the estimation of stand characteristics from remote sensing imagery remain, such as the relatively loose correlation between crown characteristics and stem dimensions in these natural forests. Furthermore there is no way to assess, from remote sensing imagery, characteristics of regeneration, of quality and of occurrence of decay or of accessibility such as soil bearing capacity or ground roughness.

Therefore the choice of the field sampling design is particularly important. Some indications are given below of the suitability and relative advantages of various types of distribution of the sample (sampling design strictly speaking) and of the possible nature, size and shape of the sampling units. These two topics are considered separately although they are in fact very closely linked: for instance the decision whether to use a one-stage or two-stage sampling design depends partly on the size of the sampling units; if the latter are relatively large a two-stage sampling design may not bring a significant increase in efficiency even in an inventory of a vast forested area.

31 Distribution of the sample

311 Unrestricted versus stratified sampling. As said in Cochran's "Sampling techniques" (2nd edition, page 99), stratification "if intelligently used nearly always results in a smaller variance for the estimated mean or total than is given by a comparable simple random sample". Stratification in forest inventory is generally performed through interpretation of remote sensing imagery prior to the field sampling (or after sampling if stratification criteria are assessed after the field sampling). It must be emphasized again that the field sampling is actually stratified only if the size of the strata can be exactly (or almost exactly) known or if, as in the case of double sampling for stratification, their size is estimated from a larger sample. Thus formulas giving the estimated variances obtained from stratified samples (such as formulas (6) or (8) of chapter III) should not be applied when limits of "strata" are drawn around a set of sampling units, and there is no further interpretation to ascertain whether all the units of these "strata" correspond to the criteria defined for this stratification (e.g. slope greater than 50%, height of the dominant trees larger than 15 metres, etc...).

The criteria for stratification must be defined in a clear and understandable form. Very refined stratification by photointerpretation is generally illusory since the possible gain in precision by comparison with a more simple classification may be more than counterbalanced by subjective biases, misinterpretations and discrepancies between photointerpreters and over time. Even in the case of a simple and easy classification, misinterpretations are possible due to low quality and the age of the remote sensing imagery; it is therefore necessary to correct the areas of the strata by a sampling procedure such as the one described in paragraph 232 of this chapter: the precision of the estimated means of the stand characteristics over the whole inventoried area decreases as the proportion of misinterpretations increases and the gain by stratification may become insignificant

compared with the total cost of the stratification work. It must be realized also that when stratification has to be corrected by a sampling procedure an exact assessment of the actual location of the strata is not possible, the estimates of their real areas becoming less precise as the intensity of the field sample is lower.

312 Random versus systematic sampling. In the case of one-stage sampling designs there is no doubt that the practical advantages of the systematic distribution of the sampling units greatly exceed its main theoretical shortcoming, that is the difficulty of estimating the variances of the results. Most of the practical advantages of systematic sampling in temperate forests are still more evident in tropical mixed forests where environmental conditions hamper field work. Among these advantages may be quoted reduction of access cost for an area unit of sample, greater certainty of objectivity in the selection of the sample (the systematic distribution of the sample leaves less room for possible modification of the location of the sampling units by the field crews) and more uniform distribution of the sample (and consequently of information) over the inventoried area (this latter advantage being more significant in areas which are surveyed for the first time). Moreover research is being pursued on the estimation of statistical error in systematic sampling and it is expected that methods based on the theory of stochastic processes will soon become available in practice. For all these reasons it is highly recommended that a systematic distribution of the sampling units should be adopted whenever one stage sampling is feasible.

In multi-stage sampling designs, the choice between a systematic and a random distribution of the sampling units has to be made at each stage of the sampling procedure. The advantages of a systematic distribution are not equally important in the various stages. Regular distribution of information within the penultimate units (within the primary units in a two-stage design) is generally not essential, while the systematic layout of the sampling units of the first stages may be particularly useful. For instance, in a two-stage sampling design where the primary units are squares of 2 kilometre sides, and secondary units strips of 2 kilometres in length and, say, 10 metres in width, the random allocation of the strips within each primary unit will not bring a significant increase in access cost but, on the contrary, the systematic distribution of the squares over the whole inventoried area may be of great value, especially if the area is surveyed for the first time.

313 One-stage versus multi-stage sampling. The main advantage of a multi-stage design in comparison with a one-stage design of the same overall sampling intensity and with the same size and shape of the (ultimate) sampling units, is that the component of the cost allocated to the access of the (ultimate) sampling units is greatly reduced. This is particularly true in mixed tropical forests where penetration is difficult. Against this the concentration of the sample resulting from a multi-stage procedure increases the variance of the estimates, and the greater the variability is between the units of the first stage, the larger is this increase in variance.

These considerations can be illustrated in a very simple and sketchy way in the case of two-stage designs (see Desabie - 1966):

(a) the variance of the estimate can very often be expressed as:

$$v = \frac{A}{n} + \frac{B}{n\bar{m}}$$

where: n is the number of primary sampling units

$\bar{m}$ is the mean number of secondary sampling units per primary sampling unit

A is a measure of the variability between primary units

B is a measure of the average variability between secondary units within a given primary unit.

(b) the cost of the sampling can often be expressed approximately as:

$$C = nC_1 + n\bar{m}C_2$$

where: C_1 is the cost of access to and reconnaissance of one primary unit

C_2 is the cost of access to a secondary unit (when the primary unit has been reached) and of recording inventory data in this unit.

It can be understood from these two formulas that v depends very much on A and n and is likely to be larger than the variance corresponding to a one-stage design with $n\bar{m}$ sampling units. On the other hand the second formula explains why C will be smaller than the cost of reaching and recording $n\bar{m}$ secondary units distributed in a one-stage design.

If acceptable estimates of A, B, C_1 and C_2 are available the two-stage design can be optimized under certain constraints using the procedure indicated in paragraph 341 of chapter III.

This simple formulation should be kept in mind when deciding between a one-stage or two-stage design. As already said the size of the ultimate sampling units is an important factor and some one-stage cluster sampling designs do not differ much in cost although they are fundamentally different as far as variance estimation is concerned. The larger and the more inaccessible the inventoried area, the more suitable a multi-stage design, but other factors are important such as the need for information uniformly distributed over the whole inventoried area and also the size of inventory units for which estimates have to be provided.

314 Equal or unequal probability in sampling. Most field sampling designs used in forest inventory consist of sampling units selected with equal probabilities (and without replacement). But there exist some efficient designs for which the probability of selection of the sampling units are proportional to their size as the one indicated in paragraph 422.122 of chapter III. When selecting such a design one has to remember that the sizes of all the units of the population considered (population of the primary units in the above-mentioned example) have to be known and listed: in certain cases the cost of the corresponding work may be too high compared with the expected gain in precision.

315 Use of an auxiliary parameter. Whenever an auxiliary parameter which is linearily correlated with the parameters to be estimated by the field sampling can be known exactly or estimated cheaply from a large sample, its use is recommended. Examples of ratio and regression estimates in double sampling have already been given in section 2 of this chapter. A classical example in forest inventory is also the use of the size of the sampling units as an auxiliary parameter for ratio estimation of the stand characteristics. It is very common in inventories of mixed tropical forests to have ultimate units of different size; for instance, if parallel strips are used as sampling units their area may vary due to the irregular shape of the inventoried area and of the relevant stratum or both, and also with the steepness of the terrain (if the dimensions of the strips are measured along the terrain and not horizontally). However when using this type of estimation, it must not be forgotten that the "ratio of the means" estimates are biased and that this bias has to be reduced to a minimum (see footnote, page 49).

32 Characteristics of the sampling units

321 Plot sampling versus polyareal sampling. Plot sampling consists of designs using area elements as sampling units or record units (with the same sampling or record unit possibly composed of two or three plots of different size for the recording of different parameters - see for an example paragraph 23 of chapter V), while polyareal sampling corresponds to point (or line) sampling designs in which the size of the recording area in each unit is a continuous function of a characteristic of the tree (e.g. its basal area in horizontal point sampling).

In this latter case there is no sampling or record unit in the physical sense and the whole population to be inventoried cannot be considered, strictly speaking, as the collection of the points or lines used as sampling "units". The practicality of polyareal sampling designs in mixed tropical forests has already been briefly discussed in paragraph 422.2 of chapter III. Cost precision studies in temperate forests have shown that horizontal point sampling is generally more efficient but there is no evidence for the time being that it is the same in the tropics. Furthermore a mere efficiency study is not sufficient and other factors have to be considered such as the reliability of the data recorded - selection of the trees to be recorded is more difficult in point sampling than in plot sampling - and the advantages of obtaining in each unit a representative picture of the forest, which is not provided by point sampling. There exist some combined point sampling designs where all trees below a given diameter (say 30 cm) are recorded provided they fall within the circular plot the radius of which is determined by this diameter and the basal area factor used in the sampling, the larger trees being of course recorded in the normal manner used in point sampling.

322 Size of the sampling units. It is commonly accepted that the coefficient of variation C_v of a given stand characteristic (parameter), (say number of trees more than a given diameter per sampling unit) is linked with the area of the sampling unit by the following empirical relation:

$$C_v = \frac{\sigma_y}{\bar{y}} = ka^{-c} \qquad (17)$$

where: σ_y is the standard deviation of the individual values of the stand characteristic y in the units of the population

$\bar{y}$ is the mean of the stand characteristic per sampling unit

a is the individual area of the sampling units

k and c are positive constants independent of a.

This relation can also be written in logarithmic form:

$$\log C_v = \log k - c \log a = K - c \log a$$

c is equal to 0.5 when the distribution of the values per unit of the stand characteristic is a random distribution, such as the Poisson distribution. This is approximately true of parameters related to the occurrence of trees of species with a very low density in mixed tropical forests (e.g. numbers of stems and corresponding gross volumes of the "mahoganies" in West Africa forests). For many other parameters in tropical forests c is found to be rather lower than 0.5.

It is interesting to compare different sizes of sampling unit in unstratified random sampling design for the same sampling intensity. In this case we have:

$$na = \text{constant}$$

where n and a are respectively the number of the sampling units and the area of one sampling unit. The percentage standard error of y (mean value per unit of a stand characteristic y) is equal to:

$$e = \frac{\sqrt{v(\bar{y})}}{\bar{y}} = \frac{C_v}{\sqrt{n}} = k' (C_v \sqrt{a}) = k'' a^{0.5-c} \qquad (18)$$

the latter expression being obtained from the empirical formula (17)

For most of the parameters in mixed tropical forests we have $C < 0.5$. It can be concluded from (18) that, for a given sampling intensity, the smaller the sampling units the better the precision. However it is useful to have in each sampling unit a fairly representative image of the forest and this can only be obtained if the sampling units have a reasonable size: a sampling unit of 0.01 ha in a mixed tropical forest for estimation of the volume of exploitable size would not be useful in this respect. In addition the total number of borderline trees in the whole sample (all sampling units) is higher for a sample consisting of a large number of small sampling units than for an equivalent sample (same total area) consisting of a smaller number of larger sampling units of the same shape. The selected size of the sampling units is thus a compromise between the conflicting requirements of the sampling precision and of the important practical aspects of representativeness of the sampling units and reliability of the basic data. An area of the sampling unit equal to 1 acre (0.4 ha) or to 0.5 ha is often considered as a suitable compromise in inventories of mixed tropical forests.

323 Shape of the sampling units

323.1 Circular versus square or rectangular plots

The main advantages of circular plots are:

- the minimum perimeter for a given area of the circle compared to other simple geometric shapes, which in turn implies the minimum number of borderline trees;

- the isotropic image of the forest around the centre given by a circular sampling unit.

Its use in temperate areas is increasing although it must be realized that, for practical reasons, the form of these plots is in fact elliptic whenever there is a slope. (Interesting devices using a range-finder and a stadia rod with adjustable sighting marks for assessment of this type of plot are mentioned in "Forest Inventory" by Loetsch-Zöhrer-Haller, Volume II, pages 324-325 and in "Dendrometrie" by Pardé, pages 190-199.)

However the difficult environmental conditions and the need for a larger size of the sampling units prevent the use of circular sampling units in mixed tropical forests (but not that of circular recording units: see below, paragraph 324.3). Square or rectangular sampling units (and also record units) are often preferred in mixed tropical forests. They may be strips of a given width (generally from 10 metres to 25 metres) along parallel lines of penetration, cut through the undergrowth, and going through all the inventoried area or through a part or a stratum of it. The width should not be larger than 30 metres - i.e. 15 metres on each side of the transect line - in order to allow for a good control of the recording operation, and the width can be measured either horizontally or along the terrain; in the first case no correction has to be made for the determination of the area of the strip, but the recording is more time-consuming and possibly less reliable because of the borderline trees; the second method may be more reliable but involves measurement of the transverse slopes and more computations. The sampling units can also be either rectangular plots, or lines of rectangular plots, the plots being, in the second case, the record units and not the sampling units. The plots cannot be used as the sampling units as the distance between two consecutive plots along the line is not sufficient to secure statistical independence with regard to the parameters to be estimated (see paragraph 322.2 of chapter III).

323.2 Form of the rectangular plots

In a study made in Cameroon it has been found that the more elongated the shape of a rectangular sampling plot of a given size, the better the precision, although this effect on the precision of the shape of the sampling units was found to be less important and less significant than the effect of their size. However this was not true for very long strips (unit areas of more than 5 hectares) and very wide strips (100 metres and more in

width) were found to give better precision. Of course the use of such very wide plots would not be possible in practice in the inventory of mixed tropical forest.

323.3 Clusters

In inventories of mixed tropical forests, sampling units are often groups or clusters of circular plots, in order to profit from the advantages of circular plots while having at the same time sufficiently large sampling units. In this case the circular plots are the recording units, and are often arranged along a straight line or a squared or rectangular line ("tracts" of some European national forest inventories). However for the same size of sampling unit, a cluster of circular plots may have a longer total perimeter (and consequently more borderline trees) than the equivalent rectangular sampling unit: for instance a cluster of five circular plots of 0.1 ha has a longer total perimeter than a rectangle of 200 metres long on 25 metres width (roughly 560 metres against 450 metres).

Once a given size of circular plot (recording unit) is chosen the unit size of a sampling unit must be ascertained, i.e. what number M of plots each sampling unit must contain. This is an optimization problem with M as one of the characteristics of the sampling design to be determined. The following paragraph gives an example of such an optimization procedure and is partly extracted from "Sampling Techniques" by Cochran (2nd edition, pages 244-247).

Let us consider an unrestricted random sampling with n equal clusters (sampling units) of M circular plots each. The variance of the mean $\bar{\bar{y}}$ per circular plot (record unit) of a given stand characteristic is equal to:

$$v(\bar{\bar{y}}) = \frac{S_b^2}{nM} \qquad (19)$$

where S_b^2 is the variance between clusters (variance among the total values of y in the clusters on a circular plot basis)

The first problem is to estimate S_b^2 from the variances among the values of y in the circular plots, i.e. S_w^2 variance among the values of y in the M plots within a cluster and S^2 variance among the values of y in the circular plots in the whole inventoried area. We have approximately:

$$S_b^2 \# MS^2 - (M-1)\, S_w^2 \qquad (20)$$

(this result being obtained by an analysis of the variance of y for the whole population).

It has been found that, in many surveys S_w^2 can be expressed by the following empirical formula:

$$S_w^2 = AM^g$$

with A and g positive constants independent of M.

If we have a cost function of the same type as indicated in paragraph 313 of this chapter for two-stage sampling designs, i.e.:

$$C = nC_1 + nMC_2$$

(where C_1 and C_2 have the same meaning as in paragraph 313, the cluster standing for the primary unit and the circular plot for the secondary unit)

then the optimization problem amounts finally to find out the values of M (and also n) which minimizes

$$v(\bar{y}) = \frac{S^2 - (M-1)AM^{g-1}}{n} \qquad (21)$$

for a given total cost: $C = nC_1 + nMC_2 = Co$ (22)

Applying the procedure indicated in paragraph 341 of chapter III, it can be easily found that the optimal value Mo of M is given by the following equation:

$$AM_o^{g-2}\left(C_2M_o^3 + C_1M_o^2 - C_1M_o^2 + C_1\right) - C_2S^2 = o$$

The corresponding value n_o of the number of clusters is determined by replacing M by M_o in the equation (22).

4 Continuous forest inventory

41 Definition and utilization

Continuous forest inventory comprises all forest inventory designs in which sampling is used on successive occasions. This definition is much broader in scope than the one of the north American CFI in which all the successive inventories use the same sample (all the sampling units are said to be "permanent" units).

Sampling on successive occasions should be considered in designing a forest inventory when, in addition to an estimate of present forest conditions, accurate determination of past growth is required and the users of this information are willing to wait the necessary and often lengthy period of time for its accumulation.

Assembling growth information in this manner presupposes that forest management will be carried out on a continuing basis. Although forest management on a continuing basis is at a very early stage in many tropical countries, and has not even been started in some cases, inventory officers should always keep in mind the need of such inventories for forest management purposes and should initiate continuous forest inventory programmes whenever the concern for forest management and the probability of making use of the results of such inventories are deemed sufficiently high. In this respect the concept of forest management must be understood in a broad sense; the monitoring of the forest cover through the use of permanent plots on remote sensing imagery represents a large field of application of continuous forest inventory which does not relate only to forest management but also to land use policy and environmental concern.

42 Description of design

421 Different types of continuous forest inventory. The objectives of repeated sampling in forest inventory are threefold:

1. to estimate characteristics of the forest present at the first inventory;
2. to do the same on the occasion of the second inventory;
3. to estimate the changes in the forest during the period between inventories.

(Note that the repetitive process can be continued and on the occasion of all subsequent inventories the previous inventory is referred to as the "first inventory".)

There are four basic ways in which the above information can be obtained:

1. A completely new sample can be drawn from the forest at the time of each inventory. The sampling units on occasion 2 are different from those taken on occasion 1.

2. The sampling points taken at the first inventory are remeasured at the second and all succeeding inventories. This is the concept of permanent sample plots and the basis of the Continuous Forest Inventory (CFI) developed in North America.

3. At the second inventory a portion of the initial sampling units are remeasured and new ones are taken. This is often called successive sampling with partial replacement (SPR).

4. At the second inventory a portion of the sampling units taken at the first inventory are remeasured.

422 Sampling with partial replacement (SPR). Of the four approaches the most efficient is the third, successive sampling with partial replacement. If repeated inventories are planned, inventory officers should design their procedures on this basis.

Only a concise summary of the design and analysis of this one method is attempted here and for more details reference should be made to Ware and Cunia (1962) as shown in the list of references. A good description of this and the other three kinds of repeated sampling are also covered in F. Loetsch and K. Haller "Forest Inventory" (volume 1, pages 259 to 277).

At the initial inventory there are two kinds of sampling units; plots measured only on the first occasion (unmatched) and plots measured at the first inventory and to be remeasured at the second (matched). At the second inventory there will be the plots taken at the first inventory and now to be remeasured (matched). In addition there will be new plots to be taken which did not appear at the first inventory (new). The following symbols for the number of sampling units and the observations are needed:

First inventory

u = number of unmatched sampling units taken at the first inventory

x_{ui} = parameter (stand characteristic) measured on unmatched sampling units at first inventory

m = number of matched sampling units taken at the first inventory

x_{mj} = parameter measured on matched sampling units at first inventory

$u + m = n_1$ = total number of sampling units at the first inventory

Second inventory

m = number of matched sampling units taken at the second inventory (same as m of first inventory)

y_{mj} = parameter (same as x) measured on matched sampling units at second inventory

n = new sampling units taken at second inventory

y_{nk} = parameter (same as x) measured on new sampling units at second inventory

$m + n = n_2$ = total number of sampling units at the second inventory.

Then:

$$\bar{x}_u = \frac{\sum_{i=1}^{u} x_{ui}}{u}$$ mean of values of the parameter per sampling unit measured on first occasion from unmatched units

$$\bar{x}_m = \frac{\sum_{j=1}^{m} x_{mj}}{m}$$ mean of values of the parameter per sampling unit on first occasion from matched units

$$\bar{y}_m = \frac{\sum_{j=1}^{m} y_{mj}}{m}$$ mean of values of the parameter per sampling unit on second occasion from matched units

$$\bar{y}_n = \frac{\sum_{k=1}^{n} y_{nk}}{n}$$ mean of values of the parameter per sampling unit on second occasion from unmatched units

a) Estimation of the means per sampling unit at first and second inventories.

1. The estimate $\bar{x}$ of the mean per sampling unit of the parameter at the first inventory is:

$$\bar{x} = \frac{m\bar{x}_m + u\bar{x}_u}{n_1} = \frac{\sum_{j=1}^{m} x_{mj} + \sum_{i=1}^{u} x_{ui}}{n_1}$$

2. The best estimate $\bar{y}$ of the mean per sampling unit of the parameter at the second inventory is given by:

$$\bar{y} = a(\bar{x}_u - \bar{x}_m) + c\bar{y}_m + (1-c)\bar{y}_n$$

where:

$$a = \frac{m(\frac{u}{n_1})r \;\frac{s_y}{s_x}}{n_2-(\frac{u}{n_1})nr^2}$$

$$c = \frac{m}{n_2-(\frac{u}{n_1})nr^2}$$

with:

$$s_x^2 = \frac{\sum^{n_1} x^2 - \frac{(\sum^{n_1} x)^2}{n_1}}{n_1 - 1}$$ $\left(\sum^{n_1} x = \sum_{i=1}^{u} x_{ui} + \sum_{j=1}^{m} x_{mj} \right.$

$\left. \sum^{n_1} x^2 = \sum_{i=1}^{u} x_{ui}^2 + \sum_{j=1}^{m} x_{mj}^2 \right)$

$$s_y^2 = \frac{\sum^{n_2} y^2 - \frac{(\sum^{n_2} y)^2}{n_2}}{n_2 - 1}$$

($\sum^{n_2} y$ and $\sum^{n_2} y^2$ being obtained similarly to $\sum^{n_1} x$ and $\sum^{n_1} x^2$)

and
$$r = \frac{\sum_{j=1}^{m}(x_{mj}-\bar{x}_m)(y_{mj}-\bar{y}_m)}{\sqrt{\sum_{j=1}^{m}(x_{mj}-\bar{x}_m)^2 \sum_{j=1}^{m}(y_{mj}-\bar{y}_m)^2}}$$

An estimate of the variance of $\bar{y}$, $v(\bar{y})$, is given by:

$$\boxed{v(\bar{y}) = a^2 \left(\frac{1}{u} + \frac{1}{m}\right)s_x^2 + \left[\frac{c^2}{m} + \frac{(1-c)^2}{n}\right]s_y^2 - 2\,\frac{ac}{m}\,rs_x s_y}$$

which can be expressed more simply as:

$$v(\bar{y}) = \frac{1-\frac{u}{n_1}r^2}{n_2-\left(\frac{u}{n_1}\right)nr^2}\,s_y^2 = \frac{c}{m}\left(1-\frac{u}{n_1}r^2\right)s_y^2$$

(b) Estimation of difference between the mean values per sampling unit of the parameter at first and second inventories.

In the case when the parameter indicated by x and y is a volume, this difference will express the growth of the stand corresponding to this volume over the period between the two inventories.

The best estimate of this mean growth per sampling unit is given by the formula:

$$\boxed{g = A\bar{y}_m + (1-A)\bar{y}_n - B\bar{x}_m - (1-B)\bar{x}_u}$$

where:
$$A = \frac{m+n\left(\frac{m}{n_1}\right)r\,\frac{s_x}{s_y}}{n_2-\left(\frac{u}{n_1}\right)nr^2}$$

$$B = \frac{m\left(\frac{u}{n_1}\right)r\,\frac{s_y}{s_x} + n_2\left(\frac{m}{n_1}\right)}{n_2-\left(\frac{u}{n_1}\right)nr^2}$$

An estimate of the variance of g is given by:

$$\boxed{v(g) = \frac{A^2s_y^2 + B^2s_x^2 - 2ABrs_x s_y}{m} + \frac{(1-A)^2s_y^2}{n} + \frac{(1-B)^2s_x^2}{u}}$$

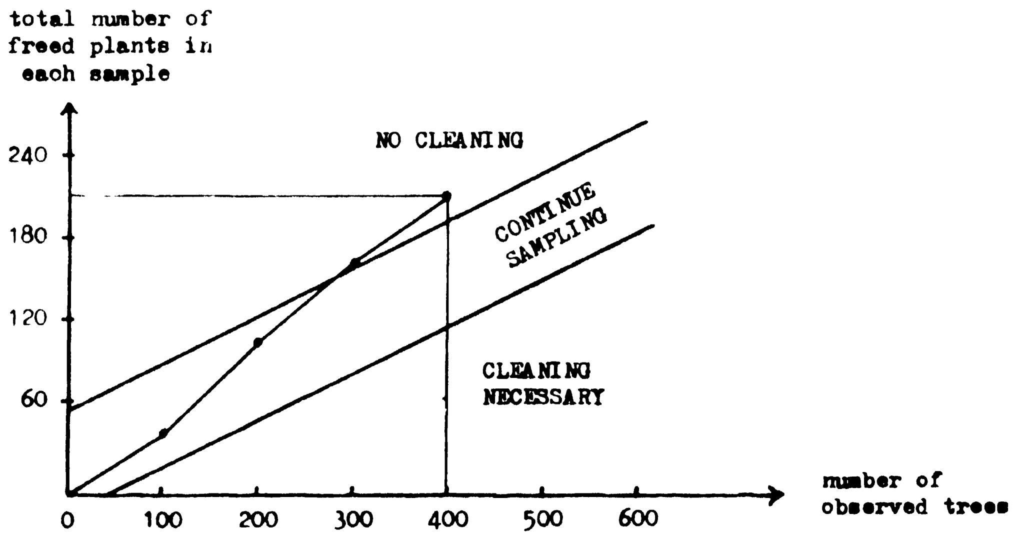
which can also be written as:

$$v(g) = \frac{1}{n_2-(\frac{u}{n_1})nr^2} \left[(1-\frac{u}{n_1}r^2)\, s_y^2 + (\frac{n_2}{n_1} - \frac{nr^2}{n_1})\, s_x^2 - 2\frac{mr}{n_1} s_x s_y \right]$$

5 <u>Sequential sampling</u>

Sequential sampling, like continuous forest inventory, also involves a series of samples but each of these samples includes <u>all</u> the sampling units of the former sample ($u = o$ whatever the sample) and in addition the time span between two successive samples is negligible so that from a forestry viewpoint all the samples can be considered as simultaneous.

The purpose of sequential sampling is to permit the taking of a relatively secure decision about a population (forest stand) from a limited number of units of this population. Let us consider the example of a planted area where it has to be decided whether a cleaning of the plants is necessary to free them from weed vegetation. Let us suppose also that this planted area can be divided into equal lines (units) of twenty plants. Lines will be selected at random to constitute the successive samples and in each sample the total number of freed plants is recorded. Each sample drawn (the second sample including all the lines of the first and some new ones, the third including all the lines of the second and new ones, and so on) will be represented by a point on a chart, the x-coordinate of this point being the size (number of lines) of the sample, the y-coordinate being the total number of freed plants of this sample. Moreover on this "sequential sampling chart" two parallel lines are drawn which divide the chart into three regions: "no cleaning", "continue sampling" and "cleaning necessary".



<u>Fig.1</u>

If the representative points of the last samples remain in the region "no cleaning" (as in figure 1) the sampling procedure can be stopped and the decision is taken not to carry out any cleaning operation. If the points stay in the region "cleaning necessary" further sampling is unnecessary and the decision is taken to begin cleaning. If the representative points are in the region "continue sampling", no decision can be taken with

sufficient security and the sampling has to be pursued.

The slopes and zero ordinates of the two parallel lines which are the basic elements of this sampling procedure are a function of:

- the distribution of the "decision parameter" in the studied population (in the above example number of freed trees per line), which is to be assimilated for the sake of simplicity to a classic distribution such as binomial or Poisson distribution;

- the minimum proportion of freed trees in a line for considering that this line does not need any cleaning treatment (say 60% or 12 trees); ("acceptable" proportion of freed trees);

- the maximum proportion of freed trees in a line for considering that this line does not need a cleaning treatment (say 50% or 10 trees); ("unacceptable" proportion of freed trees);

- the two accepted risks expressed in percentages of probability:

    - of cleaning the planted area although it has in fact a sufficient number of freed trees ("rejection" risk or "producer's risk");

    - of making no cleaning at all in the planted area although it has in fact an insufficient proportion of freed trees ("acceptance" risk or "consumer's risk").

The distribution being known and the four quantities above being decided upon, it is possible to draw the lines of the chart which will help in taking the decision. A detailed description of the design and the corresponding formulas is given in "Forest Inventory" by F. Loetsch and K. Haller (Volume I, pages 278 to 289).

Although this procedure is very attractive, it has found relatively little application in forestry, mainly for the reason that little is known on the distribution of forest parameters. In mixed tropical forests there is another drawback which results from the fact that all sampling units must be selected at random, which increases the total access cost of the sampling procedure. It has been applied in forestry for regeneration surveys and for disease and insect surveys.

ANNEX I

EXAMPLE OF TECHNICAL SPECIFICATIONS

for inclusion in a contract of aerial surveying

1. CAMERA SPECIFICATIONS

(a) Vertical photography is required to be made with single lens precision aerial camera of 21 cm focal length and 18 cm x 18 cm format. The camera must be a modern high-precision aerial camera of the Wild RC 5, RC 8, or Zeiss RMK 15/23 type, equipped with a high resolution lens capable of producing the highest quality of photography with panchromatic or infrared film. Details of the camera, lens and filters which the Contractor uses for this Contract shall be supplied to the Organization(1) and stated in the contract.

(b) Where the Contractor wishes to interpose a window or hatch cover of transparent material between the camera and the ground, he will ensure that the said window or hatch cover has been fully tested within six months of the proposed date of commencement of photography to establish that it falls within accepted tolerances for homogeneity, resolution, and freedom from distortion. A certificate of this test will be submitted to the Organization for approval with the Calibration Reports described in Section 3 of the Specifications. The contractor shall ensure that such window or hatch cover is perfectly clean and free from blemishes at all times.

(c) The overall focal plane surface of the platen of the camera shall be flat, under operating conditions, to within plus or minus 0.005 mm. The film shall be held flat in the focal plane, at the instant of exposure, to within plus or minus 0.005 mm. The camera platen shall be tested with all the operating stresses present at the instant of exposure duplicated. The platen tested shall be positively identified by having the camera cone, or magazine number of the unit, permanently and irremovably marked thereon. This identifying number shall be noted on the report of the test.

(d) Between-the-lens shutters, such that light is transmitted simultaneously to all parts of the emulsion plane when the shutter is open, shall be used. The efficiency of the shutter shall be at least 75 per cent of the marked value at the fastest speed. The speeds shall be accurate to within 10 per cent of the marked value when tested at room temperature. The results of the efficiency test and the date of the test shall be recorded.

(e) When a camera is equipped with a pressure altimeter, the altimeter shall be connected to the static system of the aircraft. The altimeter automatically recorded by the camera must be adjusted to give the same reading as the aircraft altimeter prior to the commencement of each photographic flight.

(f) When a camera is equipped with a clock for recording times of exposures, the clock shall be set to correct local time prior to each photographic flight.

2. CAMERA CALIBRATION

(a) Each camera optical unit to be used in the performance of the Contract shall be calibrated before the flying of the photography by a competent authority to be approved by the Organisation and calibration reports rendered as required in Section 3 below. The interval between calibration and photography shall be as short as possible and in no case shall exceed one year.

(1) Organisation is used hereinafter to designate the party which lets the contract.

(b) Calibration shall be carried out with the optical unit in the same condition as when used for the contract photography and with the filter fitted in the same position. After calibration, no adjustment or repair which could in any way affect the calibration shall be made. If the optical unit should be accidentally disturbed, no further photography may be taken with that camera, which must be replaced by another that has been calibrated and approved by the Organization.

3. CALIBRATION REPORTS

A calibration report for each camera used shall be submitted to the Organization and shall contain the following information:

(a) A certificate of calibration showing the name of the approved authority, date and place of calibration, the maker's serial number of the camera optical unit, the serial number of the lens and of the platen.

(b) The coordinates of the principal point of auto-collimation relative to the fiducial marks.

(c) The radial distortions of the image with reference to the principal point of auto-collimation at zero, measured outwards at intervals of not more than $7\frac{1}{2}^{\circ}$ toward the fiducial marks or reseau crosses in the format corners. (A statement of the arithmetic mean of these distortions will not be accepted by itself.) Asymmetry of the distortions may not exceed 0.03 mm.

(d) The principal distance at which these distortions apply.

(e) The distance between all fiducial marks.

(f) The mean resolution of the image as determined across two diagonals at an interval of not less than $7\frac{1}{2}^{\circ}$ by the standard method of the approved authority.

(g) All measurements shall be recorded to the nearest one-hundredth of a millimetre.

(h) These reports will be retained by the Organization.

4. SCALE

The photography will be taken from a flying height such that the mean contact scale of any exposure is .... and shall not deviate from the required height above mean sea level by more than plus or minus 5 per cent.

5. OVERLAP

The fore and aft overlap between successive photographs in each strip shall be 60 per cent with tolerances of plus 10 percent or minus 5 percent. The lateral overlap between photographs of every adjacent strip shall be 30 per cent with tolerances of plus 20 percent or minus 15 percent. However, the Organization may agree to accept, in exceptional cases, photographs where the maximum overlaps (70 per cent and 50 per cent respectively) are exceeded for reasons of terrain. Wherever variation of ground level causes a significant change in the contact scale of the photography, an increase must be made in the fore and aft overlap which must in no case be less than 55 percent, to accommodate the enlarged scale of a part or the whole of any strip. The corresponding increase in the lateral overlap, which must in no case be less than 10 percent, must be made to the whole of every strip which is so affected by height distortion.

6. CRABBING

Crab shall not exceed 5 percent or be such that it causes gaps in the stereoscopic cover of the contract area.

7. CAMERA TILT

Tilt shall not exceed 3° for any exposure. The average tilt for any section of 10 exposures shall not exceed 2° and it shall not exceed 1° for the entire photography produced.

8. COMBINED EFFECTS OF OVERLAP, CRAB, DRIFT AND TILT

(Applicable for mapping photography.) Any point at one-tenth of the width of a photograph from the lateral edge must appear in three successive photographs of the same flight line and in three photographs of the adjacent flight line.

9. FLIGHT LINES

The area shall be covered by parallel lines flown in a specified direction and these flight lines should not diverge from the prescribed directions by more than five degrees.

10. JUNCTION OF STRIPS

Where the end of a strip of photography joins the end of another strip flown in the same general direction, the overlap of the first strip over the second will be 4 photographs.

11. CLOUD

Cloud shall not lie over the principal point of any photograph nor shall it obscure any ground control point. The aggregate area of cloud and/or cloud shadow on any single photograph shall not exceed 5 percent of the area of the photograph.

12. TIME OF DAY

Photographic detail shall not be obscured by the shadows of topographic features due to the low angle of the sun, nor by the presence of "hot-spots".

13. FILM AND FILTER

This will be determined as appropriate for each contract.

14. PHOTOGRAPHIC QUALITY AND PROCESSING

(a) The photographs are required for detailed forest type mapping and photointerpretation studies and should, therefore, be of the highest photographic quality, according to the following specifications:

(b) The film emulsion and film base will be determined to suit each case. The film base shall have the minimum differential distortion and the negatives shall be free from stains, scratches, bar marks, dirt and blemishes of all kinds, and finger or static marks.

(c) Precautions must be taken to avoid distortion of the film during processing.

(d) All relevant fiducial marks must be distinct on every photograph.

(e) All automatically recorded data such as flying height, time of photography, and calibrated focal length must be clearly visible on every print.

(f) The negatives are required for contact printing and the density, contrast, and freedom from fog on the negatives is to be such that "normal" grades of paper will be suitable for the majority of the negatives without excessive shading and with reasonable times of exposure.

(g) The definition and contrast of the negatives shall be such that prints made as in the preceding paragraph and the prints supplied shall show ample detail throughout the full range of tones over the whole photograph and such that identification of detail from one photograph to another shall be possible with certainty.

(h) Prints shall be made using an electronic printer.

(i) Residual hyposulphite in any print shall not exceed 0.023 mgm. per square centimeter, while residual silver shall not exceed 0.01 gm. per square meter.

(j) Prints shall be trimmed to leave a rebate of up to 6 mm. on 3 sides. On the side where the images of instruments automatically recorded in the camera are located, the rebate should be sufficient to include these images.

15. MARKING OF FILMS AND NEGATIVES

(a) Each exposure in each flight line shall be numbered in consecutive order. This numbering shall be in the north-east or south-west corner of the negative. The numbering should not be less than 4 mm. nor more than 6 mm. in height. The consecutive numbering of exposures should be repeated for each flight line (e.g. the first three exposures in flight line 5 would be marked 5-1, 5-2 and 5-3). The numbering should include all negatives whether falling inside or outside the specified areas and whether or not conforming to the specifications, excluding only obviously useless negatives such as those completely obscured by cloud.

(b) A film shall be in one continuous length without joins, except for the leader and trailer which shall be at least 1 metre long. A film and its leader may include unrequired negatives and will be given a film roll number to be indicated by the Organization which will be shown at each end of the film.

(c) The margin of the first and last negative for each flight line shall be clearly marked with:

(i) The indication of the Organization, name of locality and the number of contract.

(ii) Number of the film roll.

(iii) Date or dates on which exposed; the month to be given by name not number.

(iv) Time of exposure in terms of local time.

(v) Number of camera optical unit and lens and the principal distance corresponding with the calibration particulars supplied under this specification.

(vi) Height above mean sea level at which exposed, in metres.

(d) Each print shall be titled in the rebate along its northern or southern margin.

(e) The titling required on each print is to be clear block lettering (between 3 mm. and 5 mm. in height for items (i) to (v) below, and between 4 mm. and 6 mm. for item (vi) below) and is to read and print in the following order:

(i) The indication of the Organization (an appropriate project designation)

(ii) Flying height above mean sea level in metres.

(iii) Camera focal length (in mm.) if not automatically reproduced on negative.

(iv) Date of photography.

(v) Number of corresponding map sheet.

(vi) Line and photograph number.

An example of complete marking is:

FAO NIC/68/509 - 3230M - 153.4mm - 6 SEPT 72 - 12 - 1-18

16 FILM REPORTS

(a) A report containing the following details and any others that are considered to be relevant shall be provided with each film:

The number of the contract
Name of Contractor
Number of film
Name of territory
Time of first and last exposure (local time)
Date exposed
The serial number of the camera optical unit, the magazine and lens.
The principal distance as given in the calibration report supplied under this specification
Lens aperture and negative numbers at which change in the aperture setting was made.
Filter. Shutter speed
Make and trade name of film, batch number and date of coating (if known)
Aircraft registration marks
Height above mean sea level and negative numbers between which changes of height took place
Weather conditions.

(b) A list of all the numbered negatives on the film in numerical sequence and in two columns, with remarks on the following lines:

PHOTOGRAPHY		REMARKS
Offered	Additional	
1-1 to 1-20		To specification
1-21 to 1-25		Some cloud
	1-26 to 1-36	Heavy cloud
1-37 to 1-40		To specification
	1-41 to 1-60	Insufficient lateral overlap; reflown.

(c) Although the information in this paragraph may not be complete on the original reports compiled in the field, it must be completed in the two copies of the final film report to be supplied.

(d) A general statement on the photographic quality.

17. <u>MARKING OF FILM CONTAINER</u>

On the side of each tin there shall be firmly fixed a label showing clearly:

1. Number of the contract
2. Name of the country or of the region (BLOCK CAPITALS)
3. Name of locality
4. Name of the Contractor
5. Date(s) of exposure
6. Film roll number
7. First and last negative numbers of each line contained on roll
8. Serial number of camera optical unit and lens.

18. <u>FLIGHT INDICES</u>

Flight line indices of the photography are required and may vary for each contract.

19. <u>ADDITIONAL SPECIFICATIONS</u>

The following clauses may be included in the body of the contract:

(a) <u>Inspection and acceptance</u>

(i) The Organization reserves the right to reject within six weeks of the delivery of the contact prints any photography which fails to meet the specifications.

(ii) Subject to other pertinent provisions of the contract, the contractor will have the option either to forego payment for rejected photography or to produce acceptable substitute photography.

(iii) If the Organization determines that certain photography is not in accordance with the specifications, or that there are gaps in the photographic coverage, the contractor shall make good such shortcomings prior to extending the photographic coverage, if so required by the Organization.

(b) <u>Additional photography</u>

Additional photography, if any, taken in the course of the contract and lying adjacent to the areas to be photographed in accordance with the indications given to the Contractor by the Organization may be offered to the Organisation. It shall be at the Organisation's discretion whether or not to accept any or all of the additional photography offered.

ANNEX II

SELECTED ANNOTATED BIBLIOGRAPHY

Only some of the most useful documents dealing with one or several techniques used in forest inventory are quoted in this bibliography. It mainly includes textbooks or manuals; articles or communications have been selected only when they were considered essential. With very few exceptions, all references are in English. When they also exist in French and/or in Spanish, this is indicated in the margin by (F) and/or (S). More French and Spanish references will be indicated in the bibliography of the corresponding versions of this manual.

(a) Forest inventory in general

Forest inventory is generally dealt with in specific chapter(s) in forest mensuration textbooks and manuals, but is the specific subject of some publications, among which the following can be quoted:

Bonnor G.M. - 1972. Forest sampling and inventories. A bibliography. Forest Management Institute, Ottawa, Ontario. Internal Report FMR-24, 27 pp.

Selected references from English language publications excluding articles on point sampling, on air photo measurements and theses.

FAO - 1967. Report of the Headquarters Meeting of Forest Inventory Experts on UNDP/SF Projects (held in Rome 11-22 September 1967). FO:SF/67 - IM 17, 259 pp.

These proceedings include communications of the participants to this meeting and the reports and recommendations of its various working committees. The most useful information given by this document has been taken up again in the "Manual for forest inventory operations executed by FAO" and in this manual.

Loetsch F. and Haller K.E. - 1964. Forest inventory. Volume 1, 436 pp.
Loetsch F., Zöhrer F. and Haller K.E. - 1973. Forest inventory. Volume 2, 469 pp. BLV Verlagsgesellschaft München - Basel - Wien.

This is strictly speaking the only recent textbook on forest inventory and it covers the whole range of relevant techniques. Tropical aspects of forest inventory work have not been neglected (as in former textbooks on forest inventory) and the bibliographies of the two volumes are very comprehensive.

Nyyssönen A. - 1961. Survey methods of tropical forests. FAO publication no. 13407.

Comparative study of the inventory methods used in the tropics in the late fifties.

Proceedings of the 1st FAO/SIDA training course on forest inventory (to be published in early 1974 by the Swedish Royal College of Forestry)

(b) <u>Purpose and planning of a forest inventory</u> (Chapter II)

Husch B. - 1971. Planning a forest inventory. FAO forestry and forest products studies No.17, 121 pp.

As stated in its preface this concise study "outlines the principal problems ... suggests a logical sequence for considering them ... also discusses briefly some of the most modern inventory techniques and their merits and limitations" but does not "cover technical methods".

(c) <u>Basic sampling techniques in forest inventory</u> (Chapter III)

Chacko V.J. - 1965. A manual on sampling techniques for forest surveys. 172 pp. Delhi. Manager of publications.

(S) Cochran W.G. - 1963 (2nd edition). Sampling techniques. 413 pp. John Wiley and Sons Inc., New York

A very clear textbook on sampling techniques, describing and demonstrating most of the sampling designs which may be useful in forest inventory.

(F only) Desabie J. - 1966. Théorie et pratique des sondages. Dunod, Paris. 481 pp.

Easy, clear book in French on sampling techniques with emphasis on demographic surveys.

Freese F. - 1962. Elementary forest sampling. Agriculture Handbook No.232. U.S. Department of Agriculture, Forest Service, 91 pp.

Very useful and practical handbook on sampling techniques for forest inventory with many numerical examples. Recommended by most of the specialists consulted when compiling this manual.

Hansen M.H., Hurwitz W.N. and Madow W.G. - 1953. Sample survey methods and theory. Volume I - Methods and applications. 638 pp. Volume II - Theory. 332 pp. John Wiley and Sons Inc., New York.

Very comprehensive book with emphasis on demographic surveys.

(F) Schumacher F.X. and Chapman R.A. - 1954. Sampling methods in forestry and range management. Durham, North Carolina. Duke University, School of Forestry. Bulletin No.7, revised. 222 pp.

Useful textbook on sampling techniques used in forestry although new methods such as point sampling and SPR are not covered.

Sukhatme P.V. - 1954. Sampling theory of surveys with applications. Iowa State College Press, Ames, Iowa. 491 pp.

Well-known textbook with emphasis on agricultural surveys

(F) Yates F. - 1960 (3rd edition). Sampling methods for censuses and surveys. 440 pp. Griffin, London.

This book is less comprehensive than Cochran's as far as the number of sampling methods and demonstrations are concerned, but gives more explanations and more numerical examples.

On point or line sampling

Grosenbaugh L.R. - 1958. Point sampling and line sampling: probability theory, geometric implications, synthesis. USDA Southern Forest Experiment Station. Occasional Paper No. 160.

Labau V.J. - 1967. Literature on the Bitterlich method of forest cruising. USDA Pacific Northwest Forest and Range Experiment Station Research Paper PNW-19.

(d) Remote sensing and mapping (Chapter IV)

(i) Photogrammetric measurements in forest inventory

Most of the references to photogrammetric measurements for forest inventory are articles and communications. An account of these references is made in the bibliography of the following documents and also of the textbooks on photointerpretation (see (iii)).

American Society of Photogrammetry - 1966 (3rd edition). Manual of Photogrammetry. George Banta Co., Menasha, Wisconsin, 1220 pp. (2 volumes).

Nielsen U. - 1971. Tree and stand measurements from aerial photographs: an annotated bibliography. Forest Management Institute, Ottawa, Ontario. Internal report FMR-X-29. 111 pp.

Spurr S.H. - 1960. (2nd edition) Photogrammetry and Photointerpretation (with a section on application to forestry). New York, The Ronald Press Co. 472 pp.

(ii) Vegetation and ecological classifications

In addition to the documents quoted in section 22 of Chapter IV the following should also be considered:

Holdridge L.R. - 1967. Life zone ecology (revised edition). Tropical Science Center, San José, Costa Rica. 205 pp.

(F)(S) Unesco - 1973. International classification and mapping of vegetation. Ecology and conservation no. 6. Paris. 93 pp.

A very recent classification worked out under the auspices of Unesco.

(iii) Photointerpretation in forest inventory

American Society of Photogrammetry - 1960. Manual of Photographic Interpretation. George Banta Co., Menasha, Wisconsin. 868 pp.

In addition to two chapters on, respectively, the procurement of aerial photography and the fundamentals of photointerpretation, a chapter of 64 pages is included on photointerpretation in forestry.

Avery T.E. - 1966. Forester's guide to aerial photointerpretation. USDA Handbook no. 308, 40 pp.

Hildebrandt G. - 1968. Bibliographie des Schrifttums auf dem Gebiet der forstlichen Luftbildauswertung, 1887 - 1968.

Howard J.A. - 1970. Aerial photo-ecology. Faber and Faber, London. 325 pp.

Very clear and useful book on the utilization of aerial photography with special reference to the study of vegetation, and a fairly comprehensive bibliography (35 pages).

Stellingwerf D.A. - 1966. Practical applications of aerial photographs in forestry and other vegetation studies. International Training Centre for Aerial Survey. I.T.C. Publications, Series B. No. 36-37-38-46-47-48.

This series of booklets contains a large number of stereogrammes showing vegetation and forest types in the tropics and in temperate zones, and is therefore very useful for training purposes.

(iv) New remote sensing techniques

IUFRO, Section 25 - 1971. Application of remote sensors in Forestry. Joint Report by Working Group "Application of Remote Sensors in Forestry", 189 pp.

This report comprises 13 communications of foresters who are specialists in remote sensing techniques and gives a good account of the application to forestry of the new techniques in 1970.

American National Research Council - 1970. Remote sensing with special reference to Agriculture and Forestry. National Academy of Sciences, Washington D.C., 424 pp.

This book, to which many American specialists contributed, provides the user with the basic technical background concerning remote sensing in general and in relation to vegetation, soil and water resources.

Krumpe P.F. - 1972. Remote sensing of terrestrial vegetation: a comprehensive bibliography. The University of Tennessee, Knoxville, Tennessee. 69 pp.

"850 references dealing with the utilization and application of remote sensing in forestry, agriculture and plant ecology, as well as closely allied fields such as land-use planning, resource inventory and management, and soils and terrain analysis."

Wilson R.C. - 1970. Remote sensing application in forestry (A report of research performed under the auspices of the forestry remote sensing laboratory, School of Forestry and Conservation, University of California, Berkeley, for National Aeronautics and Space Administration). 199 pp.

The sub-title of this report gives the following precision: "potentially efficient forest and range application of remote sensing using earth orbital spacecraft - circa 1980".

(e) Measurement considerations (Chapter V)

(i) Forest mensuration

Husch B., Miller C.I. and Beers T.W. - 1971. Forest mensuration. The Ronald Press Co., New York. 410 pp.

A recent textbook on forest mensuration with four chapters on forest inventory and 16 pages of references to relevant literature (mainly English).

(F only) Pardé J. - 1961. Dendrométrie. Editions de l'Ecole Nationale des Eaux et Forêts, Nancy. 350 pp.

Very useful and practical textbook on forest mensuration (but with very little emphasis on tropical forestry).

(ii) Volume equations

Cunia T. - 1964. Weighted least square method and construction of volume tables. Forest Science, Volume 10, No. 2. 12 pp.

First main document on the use of weighted regression for volume table construction.

Draper N.R. and Smith H. - 1966. Applied regression analysis. John Wiley and Sons Inc.

Freese F. - 1964. Linear Regression Methods for Forest Research. USDA Forest Service Research Paper, FPL 17, 138 pp.

Very clear manual on regression techniques with numerical application.

Prodan M. - 1968. Forest Biometrics (English translation by S. Gardiner of "Forstliche Biometrie")

(iii) Quality assessment and recovery studies

IUFRO, Section 25 - 1969. Proceedings of the meeting held in Reinbek, Germany, of the Working Group on "Mensurational Problems of Forest Inventory in Tropical Countries". Mitt. Bundesforsch. anst. f. Forst- und Holzw. Komm. verl. Max Wiedebusch, Hamburg.
A record of the discussions held and background papers submitted at this meeting which focused principally on quality appraisal and recovery studies.

(iv) Accessibility

Von Segebaden G. - 1969. Studies on the accessibility of forest and forest land in Sweden. Studia Forestalia Tecnica No. 76. 64 pp.

(f) Data recording and processing in forest inventory (Chapter VI)

Anderson, D.M. - 1966. Computer Programming FORTRAN IV. Appelton Century Crafts, New York. 430 pp. including appendices.

A manual written for beginners on computer programming in FORTRAN IV. Very instructive, suitable for home tuition and teaching purposes, with many graphs, exercises and comparison of FORTRAN compilers of different makes (IBM series, Univac, Burroughs, General Electric, Honeywell, etc.)

Dawkins H.C. - 1968. STATFORMS - Formats for elementary statistical calculation. Commonwealth Forestry Institute, Oxford. Institute Paper No. 41

26 predesigned forms for hand calculations in statistical techniques such as analysis of variance (Latin square) and co-variance, linear regression, stratified random sample, etc., indicating the different computational steps. Very useful for small manual calculations, instructive examples.

Dixon, W.J. - 1968. BMD - Biomedical Computer Programs. University of California Press, Berkeley and Los Angeles. 600 pp.

A collection of standard programmes (FORTRAN IV), originally written for IBM 7094 (approx. 32 K-words). Routines useful in forest inventory, especially BMD 05D (plotting scatter diagrams and histograms), BMD 06D (description of strata), BMD 03M (factor analysis), BMD 03R (multiple regression). Detailed description of computational procedures, preparation of parameter cards and output. Software available at many computer centres.

(G only) DRZ - 1969. Statistische Programme des Deutschen Rechenzentrums (statistical programmes of the German Calculation Centre), parts A and B. Deutsches Rechenzentrum Darmstadt (Fed. Rep. of Germany), Programme information PI 32 and 33. 120 pp.

A collection of statistical standard programmes (FORTRAN IV) as a complement to the BMD series. To be noted in particular NRMP (test on normal distribution), REV (comparison of regression of several strata), LIPR (check of linearity of equations). Documentation and software from the German Calculation Centre, Darmstadt, upon request.

Frayer E., Wilson W., Peters R. and Bickford C.A. - 1968. "FINSYS, an efficient data processing system for large forest inventories". Journal of Forestry, Vol. 66, No.12. 4 pp.

General description of this data processing system written in FORTRAN IV for IBM 7094/7040 computer system (32 K-words of CPU capacity required) and covers the following designs: 1. Complete enumeration (100 percent); 2. Simple random or systematic sampling; 3. Stratified random sampling; 4. Double sampling for stratification.

(F only) Guinaudeau F. - 1973. Expérience acquise par le CTFT en matière de traitement automatique des données d'inventaire (Experience gained by Centre Technique Forestier Tropical - Nogent sur Marne, France - in automatic processing of inventory data). Meeting of IUFRO Subject Group S4.02 (Forest Inventory) in Nancy (France), June 1973. Proceedings to be published. 10 pp.

The paper describes the data processing method developed at CTFT for the processing of field inventory data in tropical high forests. Examples of field sheet and output attached.

Haller K.E. - 1968. Inventory of national tropical forests - A computer programme for the processing of data. Unasylva, Vol.22, No. 89. 7 pp.

The paper gives primarily a thorough problem analysis of a data processing system for forest inventory. The system, designed for an IBM 1401, is of less importance because it is written in Autocoder language and specifically designed for an inventory in Liberia.

McCracken D.D. - 1963. Digital computer programming. J. Wiley and Sons Inc., New York, London. 240 pp.

Textbook for advanced home tuition of how to solve problems on modern digital computers. Recommended for additional reference. Useful index of subjects.

(G only) Müller K.H. and Streker I. - 1970. FORTRAN Programmieranleitung (FORTRAN Programming Manual). Hochschultaschenbücher, Vol. 804. Bibliographisches Institut Mannheim, Wien, Zürich. 140 pp.

Very handy and comprehensive manual for self tuition with application of programming in FORTRAN IV (IBM) and FORTRAN V (UNIVAC). Some basic knowledge of FORTRAN recommended.

Nilsson, N.E. - 1967. Some views on data processing problems in forest inventories. Report on FAO Headquarters meeting of forest inventory experts, Rome, FO:SF/67/M 17.

In the paper the role of data processing in forest inventory is treated and some recommendations including flow-charts for the organization of data processing are given.

(g) Considerations on inventory designs (Chapter VII)

(i) Continuous forest inventory

Ware K.D. and Cunia T. - 1962. Continuous forest inventory with partial replacement of samples. Forest Science Monograph 3, 40 pp.

Comprehensive study on SPR including mathematical formulation and cost analysis.

(ii) Sequential sampling

Chacko V.J. - 1966. Sequential sampling in forest insect surveys and diseases. The Indian Forester, Volume 92, No.4 (pp 233-239).

Theory and use of sequential sampling analysis in the case of binomial distribution (absence or presence of insects or of damage) or negative binomial distribution (contagious type of distribution applying to insect counts).

FAO TECHNICAL PAPERS

FAO FORESTRY PAPERS

1 Forest utilization contracts on public land, 1977 (E F S)
2 Planning forest roads and harvesting systems, 1977 (E F S)
3 World list of forestry schools, 1977 (E/F/S)
3 Rev. 1. World list of forestry schools, 1981 (E/F/S)
3 Rev. 2. World list of forestry schools, 1986 (E/F/S)
4/1 World pulp and paper demand, supply and trade – Vol. 1, 1977 (E F S)
4/2 World pulp and paper demand, supply and trade – Vol. 2, 1977 (E F S)
5 The marketing of tropical wood, 1976 (E S)
6 National parks planning, 1976 (E F S**)
7 Forestry for local community development, 1978 (Ar E F S)
8 Establishment techniques for forest plantations, 1978 (Ar C E* F S)
9 Wood chips – production, handling, transport, 1976 (C E S)
10/1 Assessment of logging costs from forest inventories in the tropics – 1. Principles and methodology, 1978 (E F S)
10/2 Assessment of logging costs from forest inventories in the tropics – 2 Data collection and calculations, 1978 (E F S)
11 Savanna afforestation in Africa, 1977 (E F)
12 China: forestry support for agriculture, 1978 (E)
13 Forest products prices 1960-1977, 1979 (E/F/S)
14 Mountain forest roads and harvesting, 1979 (E)
14 Rev. 1. Logging and transport in steep terrain, 1985 (E)
15 AGRIS forestry – world catalogue of information and documentation services, 1979 (E/F/S)
16 China: integrated wood processing industries, 1979 (E F S)
17 Economic analysis of forestry projects, 1979 (E F S)
17 Sup. 1. Economic analysis of forestry projects: case studies, 1979 (E S)
17 Sup. 2. Economic analysis of forestry projects: readings, 1980 (C E)
18 Forest products prices 1960-1978, 1980 (E/F/S)
19/1 Pulping and paper-making properties of fast-growing plantation wood species – Vol. 1, 1980 (E)
19/2 Pulping and paper-making properties of fast-growing plantation wood species – Vol. 2, 1980 (E)
20 Forest tree improvement, 1985 (C E F S)
20/2 A guide to forest seed handling, 1985 (E S)
21 Impact on soils of fast-growing species in lowland humid tropics, 1980 (E F S)
22/1 Forest volume estimation and yield prediction – Vol. 1. Volume estimation, 1980 (C E F S)
22/2 Forest volume estimation and yield prediction – Vol. 2. Yield prediction, 1980 (C E F S)
23 Forest products prices 1961-1980, 1981 (E/F/S)
24 Cable logging systems, 1981 (C E)
25 Public forestry administrations in Latin America, 1981 (E)
26 Forestry and rural development, 1981 (E F S)
27 Manual of forest inventory, 1981 (E F)
28 Small and medium sawmills in developing countries, 1981 (E S)
29 World forest products, demand and supply 1990 and 2000, 1982 (E F S)
30 Tropical forest resources, 1982 (E F S)
31 Appropriate technology in forestry, 1982 (E)
32 Classification and definitions of forest products, 1982 (Ar/E/F/S)
33 Logging of mountain forests, 1982 (E F S)
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61 Forest products prices 1965-1984, 1985 (E/F/S)
62 World list of institutions engaged in forestry and forest products research, 1985 (E/F/S)
63 Industrial charcoal making, 1985 (E)
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65 Forest legislation in selected African countries, 1986 (E F)
66 Forestry extension organization, 1986 (C E S)
67 Some medicinal forest plants of Africa and Latin America, 1986 (E)
68 Appropriate forest industries, 1986 (E)
69 Management of forest industries, 1986 (E)

70 Wildland fire management terminology, 1986 (E/F/S)
71 World compendium of forestry and forest products research institutions, 1986 (E/F/S)
72 Wood gas as engine fuel, 1986 (E)
73 Forest products: world outlook projections 1985-2000, 1986 (E/F/S)
74 Guidelines for forestry information processing, 1986 (E)
75 An operational guide to the monitoring and evaluation of social forestry in India, 1986 (E)
76 Wood preservation manual, 1986 (E)
77 Databook on endangered tree and shrub species and provenances, 1986 (E)
78 Appropriate wood harvesting in plantation forests, 1987 (E)
79 Small-scale forest-based processing enterprises, 1987 (E F S)
80 Forestry extension methods, 1987 (E)
81 Guidelines for forest policy formulation, 1987 (C E)
82 Forest products prices 1967-1986, 1988 (E/F/S)
83 Trade in forest products: a study of the barriers faced by the developing countries, 1988 (E)
84 Forest products: world outlook projections 1987-2000 – product and country tables, 1988 (E/F/S)
85 Forestry extension curricula, 1988 (E/F/S)
86 Forestry policies in Europe, 1988 (E)
87 Small-scale harvesting operations of wood and non-wood forest products involving rural people, 1988 (E F S)
88 Management of tropical moist forests in Africa, 1989 (E F P)
89 Review of forest management systems of tropical Asia, 1989 (E)
90 Forestry and food security, 1989 (Ar E S)
91 Design manual on basic wood harvesting technology, 1989 (E F S)
(Published only as FAO Training Series, No 18)
92 Forestry policies in Europe – an analysis, 1989 (E)
93 Energy conservation in the mechanical forest industries, 1990 (E S)
94 Manual on sawmill operational maintenance, 1990 (E)
95 Forest products prices 1969-1988, 1990 (E/F/S)
96 Planning and managing forestry research: guidelines for managers, 1990 (E)
97 Non-wood forest products: the way ahead, 1991 (E S)
98 Les plantations à vocation de bois d'œuvre en Afrique intertropicale humide, 1991 (F)
99 Cost control in forest harvesting and road construction, 1992 (E)
100 Introduction to ergonomics in forestry in developing countries, 1992 (E)
101 Aménagement et conservation des forêts denses en Amérique tropicale, 1992 (F)
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104 Forest products prices 1971-1990, 1992 (E)
105 Compendium of pulp and paper training and research institutions, 1992 (E)

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